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THE ECONOMIC IMPACT OF REVISED GASEOUS EMISSION REGULATIONS FOR COMMERCIAL AIRCRAFT ENGINES

January 1978

C. F. Day
H. E. Bertrand

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LOGISTICS MANAGEMENT INSTITUTE
4701 Sangamore Road
Washington, D. C. 20016

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16. ABSTRACT

The EPA has proposed the revision of the gaseous emission regulations first promulgated in 1973 (40 CFR Part 87) for several classes of aircraft engines. A draft notice of Proposed Rule Making (NPRM) was prepared and circulated informally outside EPA in the late summer of 1977. This report presents the results of an economic impact analysis of the proposed standards as they apply to commercial aircraft engines.

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EXECUTIVE SUMMARY

SCOPE AND PURPOSE OF THE STUDY

The Environmental Protection Agency (EPA) has proposed the revision of the gaseous emission regulations first promulgated in 1973 (40 CFR Part 87) for several classes of aircraft engines. A draft Notice of Proposed Rule Making (NPRM) was prepared and circulated informally outside EPA in the late summer of 1977. This report presents the results of an economic impact analysis of the proposed standards as they apply to commercial aircraft engines.

Our study focuses on three provisions of the draft NPRM concerning hydrocarbon (HC), carbon monoxide (CO), and oxides of nitrogen (NOx) emissions. They are:

- HC/CO control for newly manufactured engines - Standards remain at present levels for engines of 20,000 or more pounds thrust. For commercial engines between 6,000 and 20,000 pounds, a continuous transition of the standard with thrust is proposed. The implementation date for this standard is January 1, 1981. This provision is referred to as NME 81 throughout the report.
- HC/CO control for in-use engines - All EPA class T 2 and T 4 engines will be retrofitted to meet the same standards as required in NME 81 by January 1, 1985. This provision is referred to as IUE 85 throughout the report.
- NOx control for newly manufactured engines - All newly manufactured engines of 20,000 or more pounds thrust will be required to meet an EPA Parameter (EPAP) of 4.0 after January 1, 1984. A rated compressor ratio adjustment will be allowed for engines with pressure ratios greater than 25. This provision is referred to as NME 84 throughout the report.

HC/CO and NOx standards were also promulgated for newly certified engines with an effective date of 1984. The Logistics Management Institute (LMI) could identify no new core engines planned or in development likely to be certified after 1984, although some could be developed. It seems more likely that planned derivatives of presently certified engines will fill the needs of the industry during most of the 1981-1988 period. These derivative engines are treated as newly manufactured engines in our analysis.

ASSUMPTIONS

The major assumptions of the study are:

- Traffic growth - Most sources, both in Government and industry, predict substantial growth for U.S. and foreign airlines in the 1980's.
- Requirement for new aircraft - The airline industry will require a substantial number of new aircraft both to satisfy the growth in demand and to modernize the fleet.
- Regulatory policy - Although there is a continuing public debate over regulatory reform for airlines, no clear policy has emerged. LMI has assumed, therefore, that airline operations and economics will not be substantially different during the 1980's.
- Costs of pollution abatement - The LMI Airline Economics Model assumes that the costs of pollution abatement incurred by airlines will be recouped through price/fare increases sufficient to insure that return on investment is equal to: (1) regulatory rate, or (2) base case rate, whichever is lower. Further, the model assumes that abatement costs will be recouped in the year incurred.
- Impact on engine or aircraft producers - The study assumes that the regulation will have no impact on producers except as a result of decreases in airline traffic, hence airline requirements for new aircraft.

METHODOLOGY

Air carriers certificated by the Civil Aeronautics Board (CAB) and certain intrastate airlines using commercial jet transport aircraft are the principal users of commercial jet engines. The economic impact of the proposed regulations is, therefore, best measured in terms of their implications for airline operations, profit, capital requirements, and employment.

The first step in measuring these implications was to project a base case for the 1981-1988 time period, assuming no impact from gaseous emission standards. The base case included internally consistent estimates of demand (enplaned passengers, passenger miles) and supply (aircraft fleet, utilization rates, and seat miles). In other words, the fleet available employed at the projected utilization rates would generate the seat miles required to move the projected passengers over the estimated trip lengths, thus generating the projected passenger miles on a year-to-year basis.

The LMI Airline Economics Model was used to calculate base case airline revenues, expenses, profits, capital requirements, debt-equity ratios and employment. Next, costs of compliance expressed as changes in airline costs were inserted on a year-to-year basis. The model then generated the same set of airline operating and financial factors, taking into account the effect of price changes on demand. Economic impacts were derived by comparing before (without regulation) and after (with regulation) results.

AREAS OF UNCERTAINTY

The 1980's will probably be a growth period for airlines and airframe and engine producers. It is not clear, however, how many new aircraft will be desired, what type they will be, or how the airlines will finance their new purchases.

The airlines, best characterized as capital- and energy-intensive, with substantial fixed costs, seem to have overcome the limited growth and overcapacity problems that marked the first half of the 1970's. Traffic has rebounded and the last two years have been quite profitable. Still, the industry is approaching fleet modernization and expansion cautiously.

Airlines are, on the whole, highly leveraged, although long-term debt has been reduced over the last few years. The individual airlines' ability to raise outside financing varies; the total requirement is an estimated $5 to $9 billion through the mid-1980's. Careful asset management will be required and, at present, the airlines are seeking aircraft tailored to their individual route structures rather than a general purpose aircraft.

Boeing, the predominant jet transport producer, has not introduced an all-new transport in more than a decade. The final configuration for its proposed new aircraft (7X7/7N7 programs) has not been announced, primarily because the airlines cannot agree on either the body size (wide or standard) or the payload-range characteristics desired. Moreover, as the Douglas DC 9-80 program illustrates, foreign airlines are becoming increasingly important in defining transport aircraft characteristics. In the interim, Boeing production is approaching record levels, based on existing and derivative aircraft. The most popular Boeing aircraft is now the B 727-200, with a planned production rate of 11 per month for 1978. Boeing is also marketing standard and derivative models of the B 747 and plans possible B 737 derivatives. Lockheed and McDonnell-Douglas, the other U.S. producers, are also concentrating on derivatives. Thus, just what the next generation of jet transport will be is unclear at this time.

Faced with this uncertainty, the engine producers have available or are planning a variety of engines intended to cover the thrust ranges needed. "Clipped fan" derivatives of the large engines (JT 9D, CF 6, RB 211) will be available for wide body aircraft. For regular body aircraft, General Electric will certify the CFM 56 in the 20-27,000 pound thrust range, while Pratt and Whitney will certify the JT 10D (25-35,000) and a refanned version of the JT 8D, designated the JT 8D209 (18-24,000).

THE COSTS OF COMPLIANCE

Estimates of the costs of compliance with the proposed regulation were based on unit cost factors (engine price increments and operating and maintenance changes) applied to aircraft and engine projections. No projections of individual aircraft or engine types were made because of the uncertainties discussed above. Instead, LMI projected aircraft by generic type (wide body, regular body) and by number of engines (four, three, two). Average unit cost of compliance factors were developed for engines used on each of the generic types of aircraft.

The draft NPRM provides that all aircraft operating at U.S. airports must meet the emission standards, regardless of ownership. LMI therefore also developed projections of the foreign aircraft and engines affected by the regulation. The estimated costs of compliance, in 1978 dollars, are as follows:

	Total	U.S.	Foreign
	(Millions of	Dollars)	
NME 81	$ 136	$ 69	$ 67
IUE 85	573	386	187
Total HC/CO	$ 709	$455	$254
NME 84 (NOx)	825	448	377
Total Program	$1534	$903	$631

SUMMARY OF RESULTS

The proposed regulations will have only a minor impact on the airline industry in most cases. The cost of compliance, although large in magnitude, is relatively small when compared to projected airline revenues and expenses. In 1976, for example, the industry generated 192 billion passenger miles and had revenues and expenses of $17.5 billion and $16.8 billion respectively. Passenger miles are expected to be about 350 billion in the late 1980's, with correspondingly higher revenues and expenses. The estimated economic impacts are:

- Engine Price Increase	11-17%
- Aircraft Price Increase	1.6-3.2%
- Airline Fare Increase	0.2-0.77%
- Airline Profits Increase	2.8%
- Airline Capital Requirements	
Gross Capital Increase	2.7%
Outside Capital Increase	14%
- Airline Employment Decrease	
Percentage	0.30-0.48%
Cumulative Man-Years 81-88	
- Demand (Passenger Miles) Decrease	0.34-0.54%

In addition, the regulations will lead to a marginal decrease in fuel consumed, provided that the expected increase in engine efficiency at idle power settings is attained. No quantifiable impact on aircraft balance of trade could be identified.

POTENTIAL COST PENALTIES

During the analysis, LMI identified several issues about which EPA and industry have different opinions. The issues center around the current status of low emission technology, the emission levels included in the proposed standards, and the time required to develop commercially acceptable, low emission engines. These differences are not surprising and LMI has not attempted to resolve them. Ours is primarily an economic study, and, in any event, the NPRM is not a final rule-making. We developed the potential cost penalties associated with each issue, based principally on unsubstantiated industry inputs. These results should be viewed only as possible cost increments, not certainties; they are (in millions of dollars):

	Total	U.S.	Foreign
Compliance Schedule			
HC/CO Control	$281	$171	$110
NOx Control	494	267	227
Durability			
NOx Control	569	336	233
Premature Engine Removal			
HC/CO Control	7	5	2

NOx CONTROL FOR THE JT 8D

Late in the study, the DC 9-80 aircraft program using the refanned JT 8D-209 engine was announced. This program, coupled with other potential applications, indicates that JT 8D derivatives with rated thrust in the 18-23,000 pound range may be in quantity production after 1/1/84. Therefore, EPA is considering a possible revision to the draft NPRM to include such engines under the NME 84 regulations. LMI has not examined the implications of this possible change. Time was not available to collect from the producers whatever cost of compliance data may exist, or to develop an independent cost estimate.

REGULATORY IMPLICATIONS

While the economic impact of the proposed regulations on the airlines is not large, there are several factors that may require additional study. These include:

- Noise Abatement Regulations - The airlines will be required to meet noise abatement regulations by 1985. Congress is considering alternative methods for financing the modification or replacement of aircraft in the fleet which do not meet the promulgated standards. The LMI fleet projections reflect best estimates of changes related to noise abatement, but methods of financing the required modifications have not been specifically addressed.

- Producer's Financial Risk - The NOx standards included in the draft NPRM subject the engine producers to substantial financial risk. Reconsideration of the air quality justification for NOx standards, together with a delay in their final promulgation, increases this risk since no corresponding delay in the proposed compliance date is anticipated. At a minimum, the producers are being asked to expend resources for developing NOx control technology that could be employed on normal product improvement programs.

- Schedule Risks - The magnitude of the potential penalties associated with compliance dates suggests a careful review. The producers claim that the present schedules do not allow sufficient time for in-service testing of modified engines. A one-year delay in effective dates would reduce the potential risk substantially.

- JT 3D Engine and HC/CO Control - The Federal Aviation Agency fleet projections used by LMI as the basis for calculating costs of compliance indicate that approximately 200 aircraft using the JT 3D engine will be active after 1985. These B 707 and DC 8 aircraft can meet promulgated noise standards by sound treating engine nacelles or by reengining the aircraft. The draft NPRM does not include JT 3D under the HC/CO regulations. While the FAA projections do not guarantee that these aircraft will actually be in use after 1985, EPA may wish to review this situation.

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I. INTRODUCTION

THE PROPOSED STANDARDS

Gaseous emission regulations for several classes of newly manufactured (NME) and newly certified (NCE) aircraft engines were first promulgated by the Environmental Protection Agency (EPA) in 1973 (40 CFR Part 87). Specific standards were established controlling emissions of carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NOx), smoke and fuel venting. Although the standards and their implementation dates were based on the best data then available, subsequent progress reviews and air quality assessments led EPA to reconsider them. In late summer 1977, EPA prepared a draft Notice of Proposed Rule Making (NPRM), which was distributed informally to interested parties. This report contains the results of an economic impact analysis of the standards and implementation dates contained in that document.

The draft NPRM proposes a number of changes in the existing regulation. A new classification category for engines, "commercial aircraft engines", has been added. These engines, used on aircraft operated by commercial airlines and similar air carriers, have been determined significant sources of air pollution at major air terminals. Moreover, emission standards for general aviation engines (piston, turboprop, and small jet) have been revoked. The levels of allowable emissions have been modified and the effective dates have been extended. New standards for in-use engines have also been proposed. Finally, the requirement to retrofit for NOx has been deleted as technically infeasible at this time, and the threshold for HC/CO control retrofit has been reduced from 29,000 to 12,000 pounds thrust to insure maximum HC/CO emission reduction.

The major provisions of the draft NPRM considered in this study are:

- HC/CO Control for Newly Manufactured Engines - Standards remain at present levels for engines of 20,000 or more pounds thrust. For commercial engines between 6,000 and 20,000 pounds, a continuous transition of the standard with thrust is proposed. The implementation date for this standard is January 1, 1981. This provision is referred to as NME 81 throughout this report.

- HC/CO Control for In-Use Engines - All EPA class T 2 and T 4 engines will be retrofitted to meet the same standards as required in NME 81 by January 1, 1985. This provision is referred to as IUE 85 throughout this report.
- NOx Control for Newly Manufactured Engines - All newly manufactured engines of 20,000 or more pounds thrust will be required to meet an EPA Parameter (EPAP) of 4.0 after January 1, 1984. A rated compressor ratio adjustment will be allowed for engines with pressure ratios greater than 25. This provision is referred to as NME 84 throughout this report.

The draft NPRM also proposes standards for newly certified engines. Engines now in limited production or development, principally the CFM 56, M 45, CF 34, and JT10D, will meet these standards at no measurable increase in price. New engines certified after 1984 will be required to meet the same standards as for NME 84, but without the pressure ratio adjustment. Although it is possible that there are some new core engines planned that would be certified after 1984, we could not identify any. It is more likely that derivatives of existing engines will be certified after 1984; these have been treated as newly manufactured engines in this study.

STUDY METHOD

The kinds of economic impact quantified in this analysis include changes in:

- Aircraft and Engine Prices
- Airline Fares
- Demand for Air Transportation
- Airline Profits and Capital Requirements
- Airline Employment

Other effects were examined qualitatively, such as energy consumption and balance of trade issues.

In general, the impacts were quantified as differences from a base case that assumed no economic impact from gaseous emissions regulations. The base case was projected over the 1981-1988 time period by means of internally consistent estimates of the airline fleet, enplaned passengers, passenger miles, and aircraft utilization, developed from the best available information. These inputs were used to generate expected airline revenues, expenses, profits, capital requirements, and employment for 1981-1988.

Inputs from engine producers, airlines, and EPA were examined to determine the costs of compliance with each phase of the proposed regulations: NME 81, NME 84, and IUE 85. Both capital costs (increases in engine or part prices) and operating and maintenance costs incurred by airlines were considered. These cost increments were time-phased and used as inputs to LMI's Airline Economics Model, which generated total industry operating and financial data similar to the base case calculations. The differences from the base case were then analyzed to obtain the economic impacts.

AREAS OF UNCERTAINTY

The cost of compliance and the economic impact of the proposed regulations are directly proportional to the number of aircraft and engines controlled. This, in turn, is largely dependent on the actions taken by both domestic and foreign airlines over the next decade or so. Unfortunately, the airlines' options are somewhat unclear at this point. The current emphasis on regulatory reform may change the ground rules for doing business by the 1980's. The number and type of aircraft desired by the airlines and their methods of financing new purchases are all uncertain. The costs of meeting the present noise abatement regulations are also unknown. Nevertheless, fleet forecasts are a prerequisite for estimating costs and economic impact.

We believe we have used the best available data to develop our fleet forecast. The Federal Aviation Agency (FAA) integrated 10-year aviation forecast, which includes aircraft inventory and utilization, passengers, passenger miles and departures, was used to construct the base case. Yearly figures for aircraft retirement and acquisitions were developed from a composite of estimates originally prepared by EPA, FAA, and the Air Transport Association (ATA). No estimates were attempted by specific aircraft types (e.g., Boeing 737), but the generic classes of aircraft were used. Aircraft types are grouped by body cross section (wide body, regular body) and by number of engines (four-engine, three-engine, and two-engine).

Even with these generic classifications, there is still uncertainty. The three major airframe producers in the U.S., Boeing, McDonnell-Douglas, and Lockheed are all concentrating on derivatives of their present models. It is important to note that Boeing has delayed final announcement of its proposed new aircraft program (7X7/7N7), largely because of the airlines' lack of agreement on payload-range characteristics and body size. When this aircraft is announced, it will be the first all-new Boeing aircraft in more than a decade.

Engines and airframes are carefully matched to obtain optimal aircraft performance. Because the characteristics of the long awaited "next generation" of aircraft are unknown, the three major engine producers (General Electric, Pratt and Whitney, and Rolls-Royce) have available, or are developing, "clipped fan" versions of their engines suitable for wide body aircraft. These are the CF 6, the JT 9, and the RB 211. In addition, GE is developing the CFM 56 (with SNECMA) in the 22-27,000 pound thrust range, and Pratt and Whitney is developing the JT 10D, planned for the 25-35,000 pound range. Neither engine has a confirmed application on an aircraft at this time, although Boeing and CFM 56 International will certify a B 707 aircraft using the CFM 56. This combination seems aimed more at a potential reengining market than at major new aircraft sales.

Thus, with few exceptions, both the airframe and engine manufacturers are concentrating on derivatives, rather than all-new products. Further, the technology incorporated in wide body aircraft and their engines is viewed as advanced enough to survive with normal product improvement through the 1980's. Finally, since airlines tend to control costs and investments by standardizing engine "families" to the extent feasible, aircraft producers are offering wide body aircraft with suitable engines manufactured by each of the three engine producers.

For these reasons, LMI has not attempted to estimate the sales of any particular engine type, but has instead estimated the number of engines required to support each generic class of aircraft. Costs of compliance were calculated from factors developed for each class of aircraft based on inputs from engine producers and airlines.

Because the draft NPRM stipulates that all aircraft operating to or from U.S. airports will be required to comply with the proposed standards, LMI developed estimates of the numbers of aircraft and engines in foreign fleets that will be affected. These estimates were used to estimate the cost of compliance incurred by foreign operators.

TECHNOLOGICAL FEASIBILITY OF THE PROPOSED STANDARDS

In the course of this study, several issues were identified that could have major consequences for costs of compliance and economic impact. They are: the emission levels of the proposed standards, the status of low emission technology, and the time allotted to develop commercially acceptable engines to meet the standards.

The proposed emission standards and their effective dates were developed by EPA, based on the best data available from a variety of sources, including other Government agencies and the engine producers themselves. EPA has judged both the standards and the effective dates as technologically and economically feasible, but the engine producers disagree with some provisions of the draft NPRM and believe that EPA has not fully considered their development and production problems. LMI has not attempted to resolve these technological issues because, first, such a resolution is inappropriate in an economic study, and second, the NPRM is a proposal, not a final rule-making. We have instead identified the issues and estimated the potential increase in costs of compliance associated with each.

NOx STANDARDS FOR THE JT 8D ENGINE

While the study was in progress, McDonnell-Douglas announced its decision to produce the DC 9-80 aircraft, as a result of firm orders from several European airlines and one U.S. carrier. The aircraft, which will use the JT 8D-209 engine rated at about 19,000 pounds, has substantial market potential, particularly with further growth.

The 20,000 pound threshold for NME 84 was established essentially to exempt the JT 8D on the theory that only a few such engines would be produced each year after 1984. The refanned -209 model has normal growth potential and could be used for other than DC 9-80 applications. Its high degree of commonality with other JT 8D engines, coupled with improved fuel consumption, make it attractive to the airlines. This apparent revival of the JT 8D with a potential for significant sales after 1984 has led EPA to reconsider the 20,000 pound threshold .

LMI has not considered the impact of changing the NME 84 NOx standard. The -209 model became an issue too late for cost of compliance data to be collected from Pratt and Whitney or for an independent estimate to be developed. We have assumed that the 20,000 pound threshold will not be changed.

REPORT ORGANIZATION

Chapter II of this report discusses some of the limitations of present low emission technology and how they might affect the development of commercially acceptable aircraft engines in time to meet the proposed standards. Chapter III reviews the status of the air transport industry and shows the development of the base case and the costs of compliance and the use of the LMI Airline Economics Model to estimate the economic impacts of NME 81, IUE 85, and NME 84. Chapter IV describes several regulatory implications of the draft NPRM suggested by the analysis in Chapter III. Two appendices are included: Appendix A, which develops the base case and costs of compliance in detail and Appendix B, which is a detailed estimate of costs prepared for LMI by Pratt and Whitney.

II. STATUS AND PROSPECTS OF LOW EMISSION TECHNOLOGY

INTRODUCTION

Analysis of the economic impact of EPA's proposed emission standards is directly dependent on estimates of the costs of compliance with those standards. Compliance costs, in turn, are related to the present status of low emission technology and the amount of time available to correct existing problems. The emission levels and effective dates contained in the draft NPRM were established only after careful consideration by EPA of their technical feasibility and the amount of development time required. The EPA staff had available to them the results of two NASA-sponsored programs, the Pollution Reduction Technology Program (PRTP), and the Experimental Clean Combustor Program (ECCP), and data from engine producers. In addition, the NPRM itself is merely a proposal and comments from all interested parties are invited before a final ruling is made.

Each of the three major commercial engine producers, General Electric, Pratt and Whitney, and Rolls-Royce, has taken exception to one or more of the provisions of the draft NPRM. The most serious disagreement centers around the status of low NOx technology and the time required to develop a commercially acceptable engine. LMI did not attempt to resolve these differences, but rather to identify the important time-technology issues and to estimate the potential compliance cost associated with each.

LOW EMISSION TECHNOLOGY

The modern turbofan engine used on commercial aircraft is a highly complex but reliable piece of equipment. These engines are operated between 3000 and 4000 hours per year and, when mature, do not normally require even yearly maintenance. Many JT 3D engines have operated 20,000 hours between overhauls and the high-time JT 8D and JT 9D have 13,000 and 10,000 hours, respectively. The CF 6 and RB 211, are less mature, but improvements in time between overhauls (TBO) can be expected.

A turbofan engine is made up of three major sections: a low temperature section (fan and compressors), a combustor section, and a high temperature section (turbines). Outputs of each section are closely balanced with the input requirements of the section they support. While there is generally growth potential in every new engine, it is never achieved by deliberately oversizing components since this would degrade performance and durability. Therefore, any changes required in a production engine must be accomplished within rigid space limitations and must consider the output-input matching of components.

The combustor is the heart of a turbofan engine. Figure 1, supplied by Pratt and Whitney, shows a schematic of a conventional combustor. Air, under pressure, is mixed with atomized fuel to support combustion. Additional air is used to cool the products of combustion so that the combustor output matches the desired turbine inlet temperature. Part of the energy thus generated is used by the turbines to drive the compressors and fan, while the balance is usually mixed with bypass air and expelled to achieve the desired thrust.

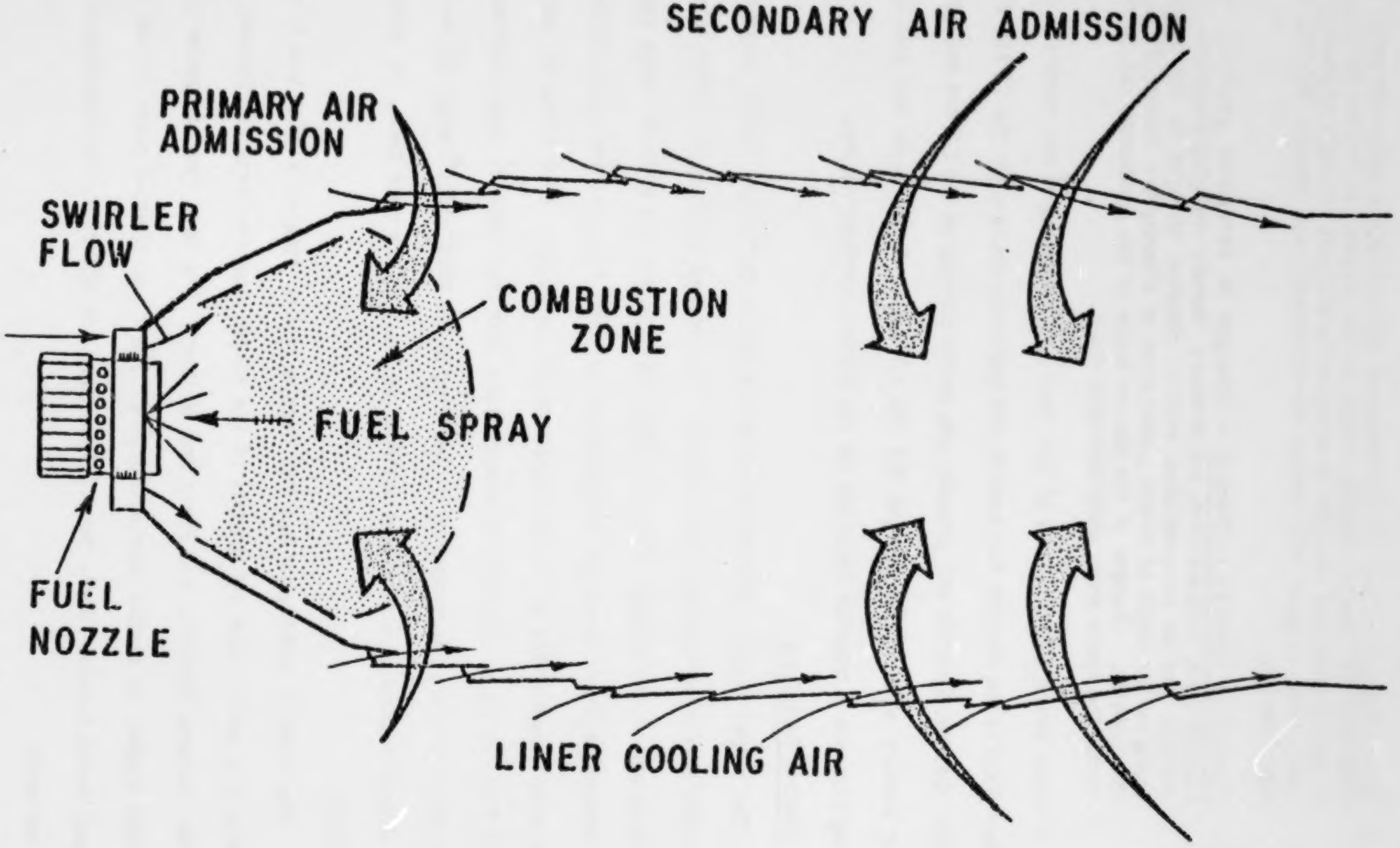
The proposed changes in emission standards all involve combustor changes. Unfortunately, HC and CO are essentially low temperature, low power problems, while NOx is essentially a high temperature, high power setting problem. Thus, the technology required for HC/CO alone (NME 81) may not lead to significant reductions in NOx. Similarly, NOx control techniques alone may not control HC/CO. Since NME 84 involves the control of all three simultaneously (along with smoke) the technology required becomes quite complex.

HC/CO Control Techniques

The engine producers, both privately and under NASA sponsorship, have examined a variety of control techniques. For HC/CO control, these have included:

- Fuel Injector Changes - The major problems with HC/CO emissions occur at low power settings, principally idle and taxi. The fuel nozzle and its shroud can be redesigned to achieve improved combustion efficiencies at these low power settings.

SCHEMATIC OF CURRENT COMBUSTORS


SECONDARY AIR ADMISSION
PRIMARY AIR ADMISSION
SWIRLER FLOW
COMBUSTION ZONE
FUEL SPRAY
FUEL NOZZLE
LINER COOLING AIR

Courtesy Pratt & Whitney

FIGURE I

- Sector Burning - Fuel injector changes will not reduce emissions sufficiently for some engines. Sector burning, simply stated, allows fuel to flow to only a portion of the nozzles, and restricts combustion to one part or sector of the engine. This restriction, coupled with improved efficiency, will reduce HC/CO emissions significantly.
- Combustor Geometry Changes - Changes in combustor geometry will alter burning time, temperatures, and pressure, thereby changing emissions. Geometry changes can be accomplished without physical changes to the combustor by changing the depth of nozzle penetration or altering the conical shrouds around the injector. Changes in the size or shape of the combustor can be made only within the space constraints discussed above.

In some cases, combinations of the three basic approaches are required. Pratt and Whitney plans to use aerated fuel nozzles and geometry changes for the JT 8D, JT 9D, and JT 10D. General Electric will probably use sector burning on the CF 6–6 and CFM 56 and sector burning with nozzle changes for the CF 6–50. Rolls-Royce will also use sector burning plus new combustor materials for the RB 211 and Spey engines.

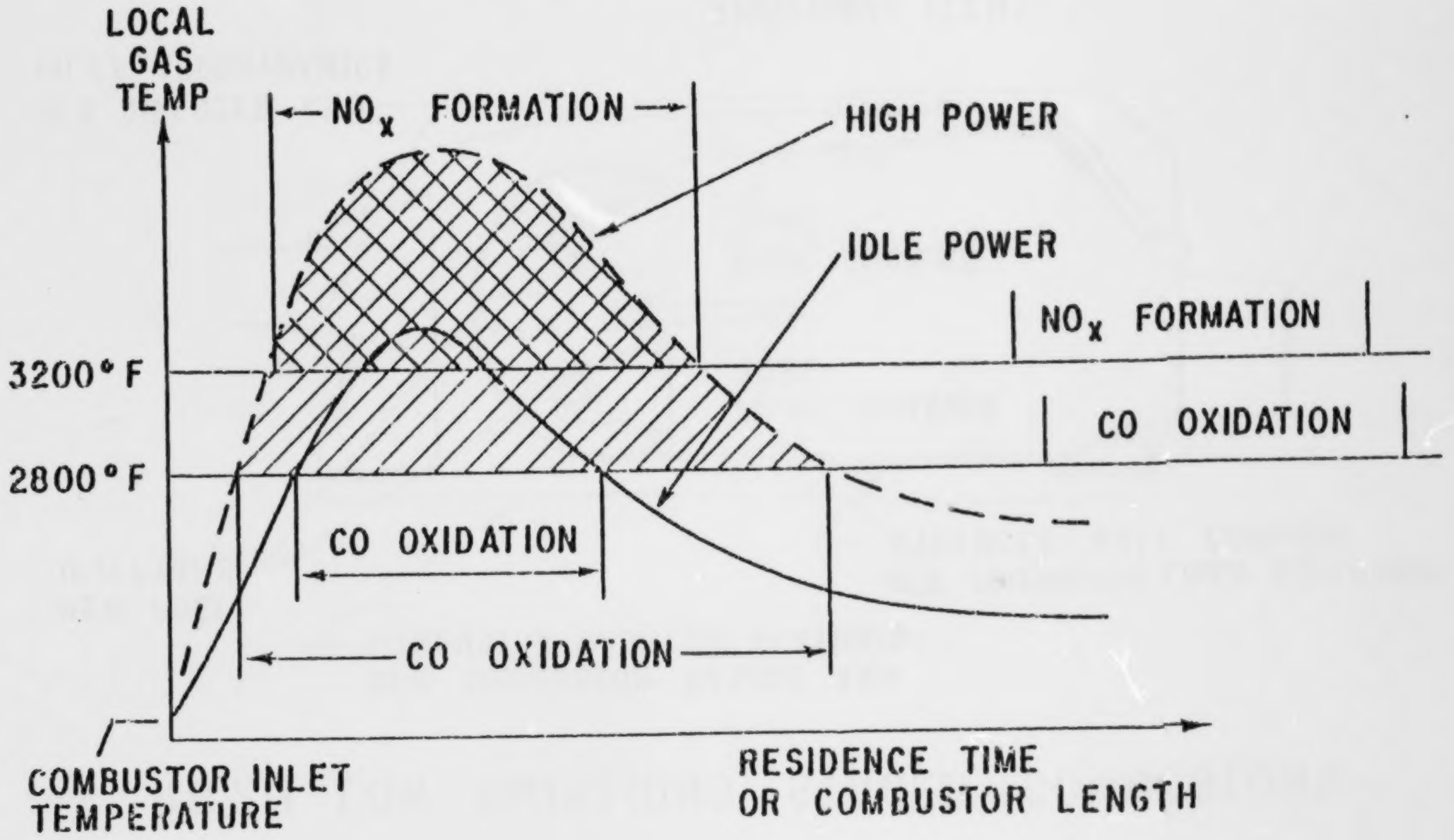
NOx Control Technique

The staged burner, demonstrated in the NASA PRTP and ECCP programs, is the producers' preferred approach for NME 84. The staged combustors tested in the NASA programs are very complex. Figure 2, supplied by Pratt and Whitney, helps explain why. The schematic shows local gas temperature patterns for a conventional combustor and notes the temperatures at which pollutants are produced. NOx forms at temperatures above 3200°F, while CO forms at temperatures less than 2800°F. Both pollutants can be reduced if the time the combustor is operating in the 2800°-3200° range can be increased. The staged combustor is the best method, at least in the near term, for achieving this condition.

This type of combustor has two burning zones (stages), a pilot and a main zone. Figures 3, 4, and 5 show schematics of the staged burners presently planned by Rolls-Royce, General Electric, and Pratt and Whitney. The first two companies plan to use radially staged, or double annular burners. Pratt and Whitney plans to use the axially staged Vorbix burner. While the configurations are different, the principles of operation are the same.

NOMINAL COMBUSTOR GAS TEMPERATURE VS RESIDENCE TIME INDICATING NO_x AND CO ACTIVITY

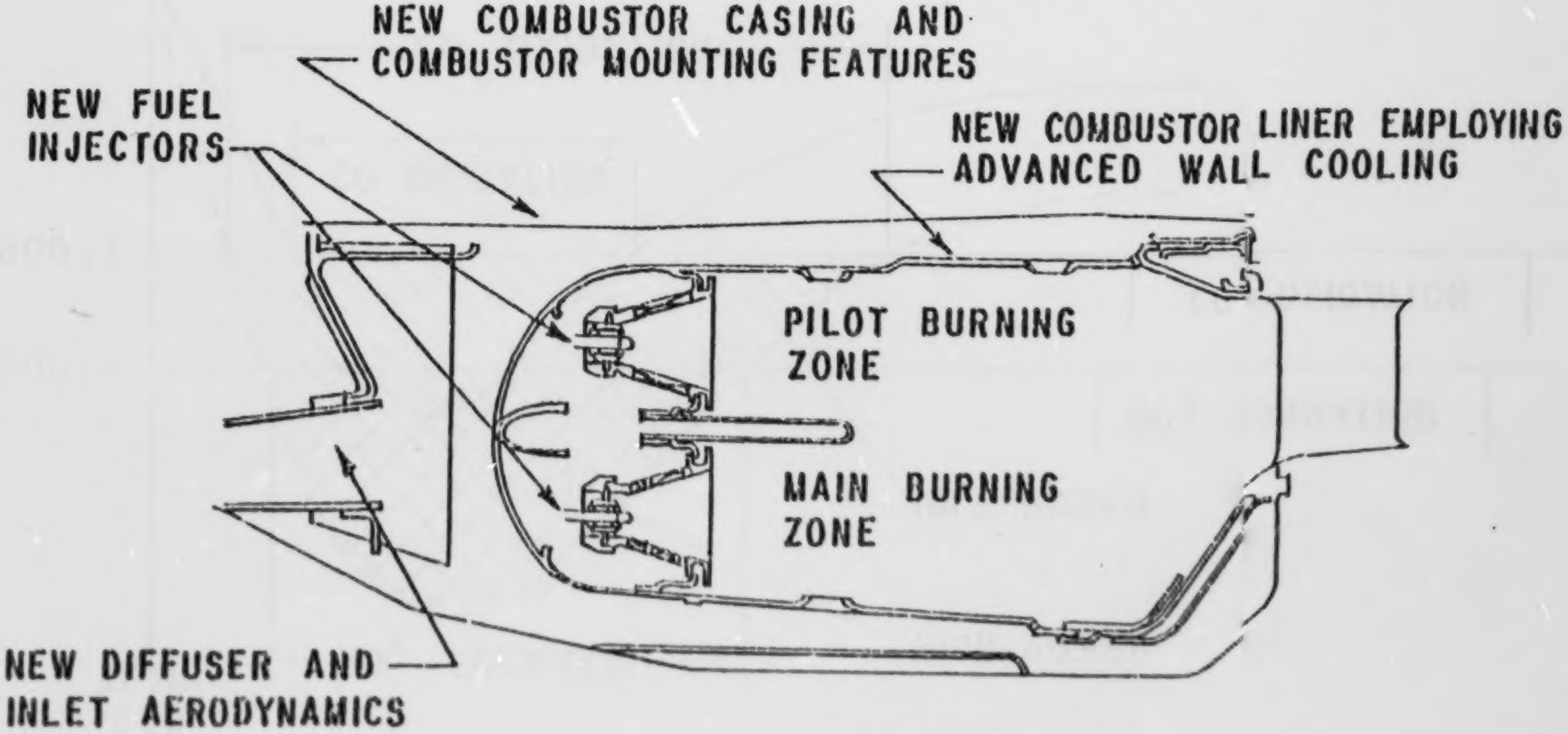
CONVENTIONAL COMBUSTORS



Courtesy Pratt & Whitney

FIGURE 2

RB211 LOW EMISSIONS STAGED COMBUSTORS

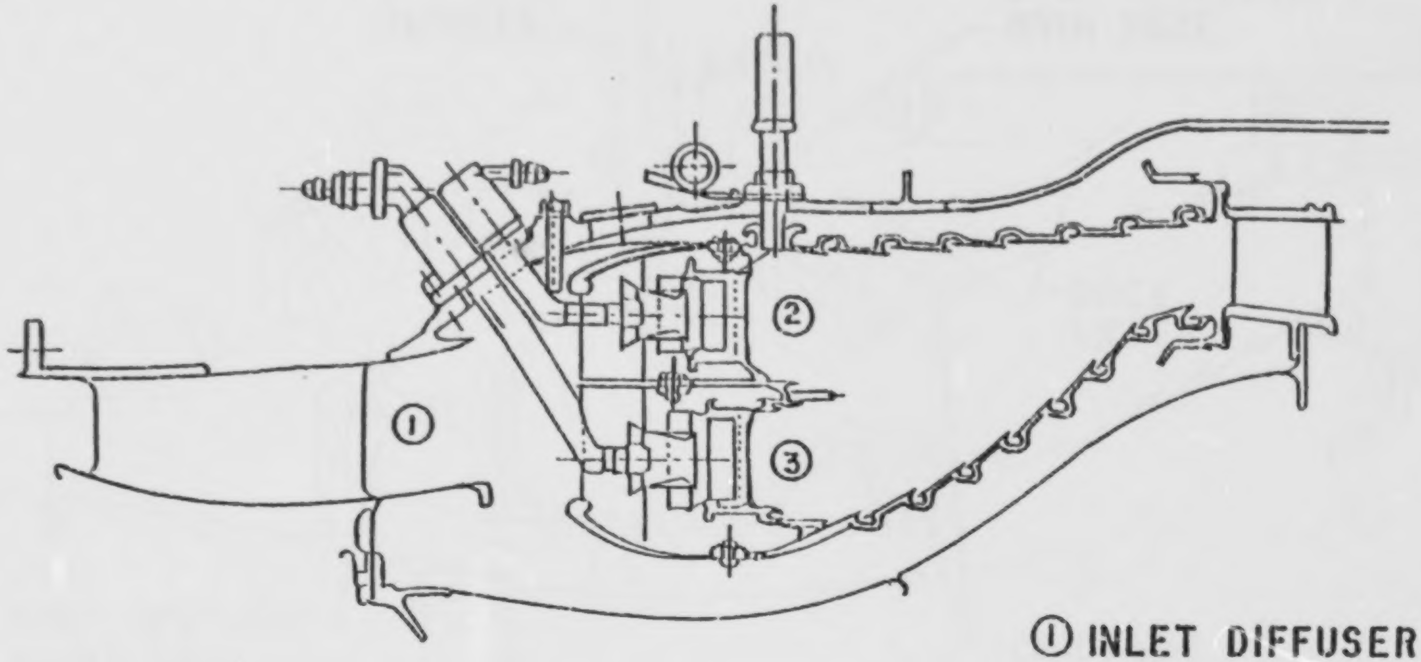

NEW COMBUSTOR CASING AND COMBUSTOR MOUNTING FEATURES
NEW FUEL INJECTORS
NEW COMBUSTOR LINER EMPLOYING ADVANCED WALL COOLING
PILOT BURNING ZONE
MAIN BURNING ZONE
NEW DIFFUSER AND INLET AERODYNAMICS

ADDITIONAL ITEMS:
NEW FUEL CONTROL SYSTEM
NEW EXTERNAL FUEL MANIFOLDS

Courtesy Rolls-Royce Ltd.

FIGURE 3

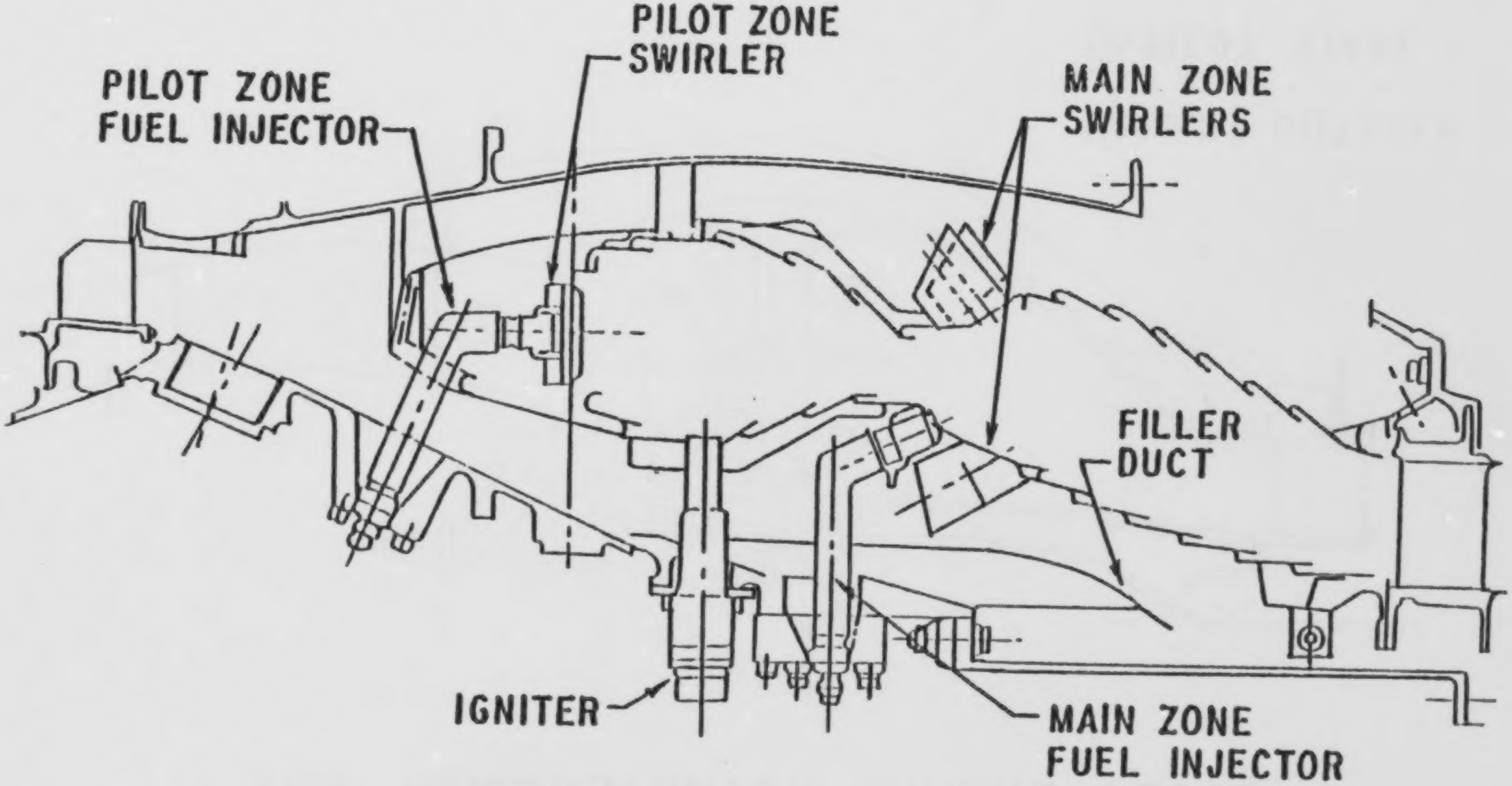
DOUBLE ANNULAR CF6-50 COMBUSTOR FOR DEMONSTRATOR ENGINE TESTS


①
②
③
① INLET DIFFUSER
② PILOT STAGE
③ MAIN STAGE

Courtesy General Electric Co.

FIGURE 4

ECCP PHASE III VORBIX COMBUSTOR


PILOT ZONE
FUEL INJECTOR
PILOT ZONE
SWIRLER
MAIN ZONE
SWIRLERS
FILLER
DUCT
IGNITER
MAIN ZONE
FUEL INJECTOR

Courtesy Pratt & Whitney

FIGURE 5

The pilot stage will receive 100% of fuel flow during idle (akin to the sector burning concept), but only 20% of total fuel flow at high power (takeoff). Thus, two sets of fuel nozzles are required, one for the pilot zone and a second for the main zone. The main zone would burn a leaner air-fuel mixture, thus reducing temperatures. The NASA programs demonstrated that the staged burners will reduce emissions. Engine tests under ECCP are in progress.

Potential Problems

Many problems remain to be solved before any of the HC/CO or NOx technologies can be incorporated into a commercially acceptable engine. The main concerns are: combustor durability, combustor temperature patterns and output profiles, fuel purging systems for sector burning and staged combustors, fuel control systems, buildup of carbon deposits (coking) on test burners, and the overall complexity of the staged burner. The dramatic increase in the number of fuel nozzles by a factor of three or four, coupled with potential altitude relight problems, also present potential safety problems. LMI believes that there is a major difference between an engine that works and a commercially acceptable engine. The staged burners are vastly more complex than those used today. We reviewed these potential designs with the engineering staff of several airlines (domestic trunks and international carriers) in order to assess potential maintenance problems.[1] All agreed that costs would increase, possibly substantially, although none had enough information to provide quantiative estimates. Their concerns centered on: increased complexity of both the combustor and the fuel management system, the increased number of nozzles, and potential safety problems with fuel line leaks or cracking, combustor life, and the ability to repair combustors.[2] In addition, the airlines agreed that hot section maintenance makes up from 60% to 80% of total maintenance cost for large engines. Failure of burners to perform as designed because of coking or other reasons is therefore quite serious.

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[1] Pratt and Whitney's assessment of potential maintenance problems is contained in Appendix B. While the cost estimates may be biased, the discussion is typical of airline opinion.

[2] Airlines buy very few new combustors for today's engines. Instead, combustors are repaired and most combustor maintenance labor occurs in the welding shop. New combustors are often required, however, if the dome area needs repair.

WHEN CAN THE PROPOSED STANDARDS BE MET?

LMI's discussions with engine producers identified several time-related technological issues that could affect the cost of compliance: the emission levels established in the standards and the effective dates. All the engine producers agree that significant reductions can be achieved, but that not all engines can meet all the standards in the draft NPRM. None of the companies believes that the 1984 deadline can be met without seriously curtailing in-service evaluations of modified engines. General Electric is the most optimistic, projecting 1/1/85 for deliveries of a low NOx engine with "adequate" service testing.

Idle Power Setting

The compliance test procedures proposed require that emissions be measured at four power points, including idle. Since total cycle HC and CO emissions are highly dependent on the idle power setting selected, the definition of "idle power" is critical for two reasons: (1) meeting the specified HC and CO standards, and (2) providing enough margin for engine-to-engine variation to insure that all, or substantially all, engines produced meet the standard.[3]

EPA is presently recommending that the idle definition be expanded to state explicitly that the engine will be tested at the minimum setting used in practice (by airlines) with simulated minimal accessory influences. The same engine, however, may be used on aircraft produced by different manufacturers using different idle settings and accessory offtakes. Figure 6, supplied by Rolls-Royce, shows the impact on "uninstalled thrust," that is, engine output without offtakes, for a B 747 and L 1011 equipped with RB 211 engines. Thus, the recommended idle setting (between 4% and 5%) is actually a greater percentage of takeoff thrust.

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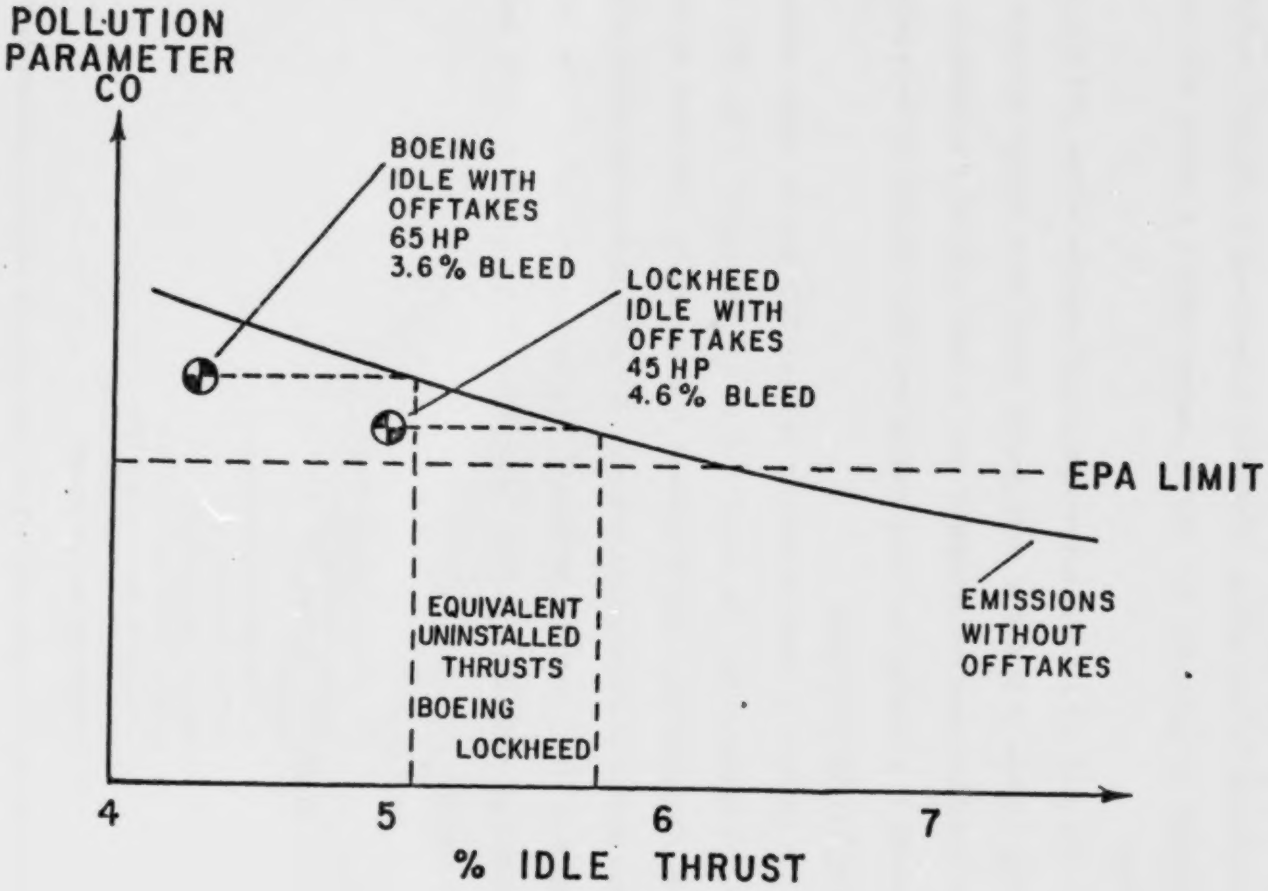
[3] EPA considers the standards as maximums and expects the manufacturers to design to less than standard emission to account for engine-to-engine variations.

SIGNIFICANCE OF AIRCRAFT OFFTAKES



Courtesy Rolls-Royce Ltd.

FIGURE 6

The standard for HC and CO is a constant, while idle setting varies; the lower the setting the more stringent the standard. The precise setting required has an impact on the margin for variation available. Rolls-Royce, for example, has been assuming the ICAO-recommended 7% idle setting. What they believed was an adequate margin (two standard deviations) for advanced low HC/CO designs became a deficit with lower idle power settings.

The draft NPRM does not recognize that retention of the 1973 standard for HC and CO (for engines of 20,000 or more pounds thrust) and a revised definition of idle setting from "manufacturers recommended" may, in fact, establish a considerably more stringent standard. It is possible that more development time and cost will be required.

Engine Development Cycle

In addition to these differences between EPA and the engine producers, there are also differences within the industry as to the practicality of the 1981, 1984, and 1985 dates. To appreciate these differences, it is valuable to understand the steps in a normal engine derivative development program. While the terminology differs slightly among the companies, the functions performed are largely the same. The following list of development steps is taken from General Electric's submission on the double annular low NOx engine:

- Prototype
  - Component Development
  - Engine Development
- Production Engine
  - Design
  - Component Development
  - Engine Development
  - Engine Flight Tests
  - Engine Qualification Tests
  - Controlled Service Use Test
  - Preparation for Manufacturing
  - Production and Shipment

Neither of the U.S. manufacturers believes that the staged combustor developed under the NASA programs can be considered a prototype, since considerably more development is required. GE's schedule, the most optimistic of the three companies, shows prototype components by the end of 1978 and a prototype engine by the end of 1979. The producers were also in general agreement on the key steps remaining to be completed. These are:

- Design Definition
- Component Development Testing
- Engine Development Testing
  - Performance
  - Cyclic Endurance
- Engine Flight Testing
- Certification Testing
- Flight Service Evaluation

Service Tests

From the producers' perspective, the schedule problems may prevent adequate service testing for both NME 81 and NME 84 engines. A service test program is designed to minimize problems once a modified engine enters commercial service. It is necessary because the engine manufacturer can only simulate service conditions during the engine test and flight test phases of development.

After FAA approval of a proposed engine change, a pilot lot of parts is produced for service program use. Usually, several airlines are asked to participate in the evaluation so that a broad spectrum of commercial experience (differing route structures and operating procedures) can be obtained. In general, the parts are provided to the airline at no cost, but the airline assumes part of the risk should a failure result in damage to other parts of the engine. The engine producer also assumes part of this risk under the terms of the applicable engine and parts service policy.

All engines and parts carry a limited time warranty against defects in material and workmanship. Normally, engine and parts service policies provide some degree of protection for virtually the life of the engine. The JT 9D, for example, is protected by a 100% parts credit allowance and a 100% labor allowance when both parts and engine have less than 2000 hours of operation. After 2000 hours, prorata material and labor protection is provided for a limited period of time. A variety of other plans and guarantees are available, but at some cost to the user.

The service test program is thus a joint understanding between the engine producer and at least one (usually several) airlines. The time required to conduct an adequate service test has become an issue. The producers have programmed a minimum of two and one-half years for NME 84 engines. GE and Pratt and Whitney have programmed a one-year service test for NME 81 engines, but would prefer a two-year test. Rolls-Royce will not be ready to certify the RB 211 with sector burning until mid-1981, and service testing could not start until after certification.

The question remains whether or not the two- to three-year service test program desired by the producers is reasonable. Clearly the time allotted should be sufficient to identify and correct serious faults. To achieve this, the test engines should be in the field at least as long as normal TBO, and perhaps high time engines should have substantially more hours and cycles than average TBO requirements. A review of 1976 CAB statistics shows that an engine mounted on the indicated aircraft for the entire year would have accumulated the following hours and cycles:

Type Aircraft	Hours	Cycles
B 747	3500	900
DC 10/L 1011	3150	1275
B 727	3140	2165
DC 9/B 737	2920	2720

These statistics indicate that the mature engines, like the JT 8D and JT 9D, could normally go more than a year without engine (or combustor) overhaul, and that the less mature RB 211 and CF 6 would normally be overhauled within the year. Both these engines, under normal conditions, are expected to improve their average TBO's by 1980. GE, for example, plans improvements which should extend normal maintenance intervals to more than one year, based on the average cycles per aircraft cited above.

Another method of evaluating the reasonableness of the two- to three-year service test programmed for low emission engines is to examine some recent examples. LMI asked Pratt and Whitney to submit data on the service tests associated with both the

JT 8D and JT 3D smoke retrofit programs as well as the problems associated with JT 9D design changes. These smoke program results were discussed with several participating airlines. In addition, General Electric submitted technical data and schedules for two proposed modifications of the CF 6 engine.

JT 8D Smoke Program

Work on smoke reduction was undertaken at Pratt and Whitney to meet a military requirement for attack aircraft operating in Vietnam. This work was the basis for a reduced smoke burner can for the JT 8D engine. In 1968, 59 sets of burner cans were released to a total of 10 airlines for service evaluation. The program was terminated in July 1971 after 273,400 hours of experience were accumulated. The high time set had 7000 hours and the high cycle set had 10,200 cycles and 6,000 hours. The program did not, however, follow normal procedures. The new burners were incorporated into production engines in August 1969, and modified parts were made available for retrofitting in-use engines by February 1970, both well before the completion of service tests.

LMI discussed this program with two of the airlines involved. Both experienced significant problems. The first reported a considerable shift in burner exit temperature profiles, which caused increased turbine maintenance and resulted in the failure of about 85% of converted engines to pass the maintenance quality control checks required by FAA. The converted engines also experienced off-idle stall problems and the rate of acceleration was reduced. These problems were solved, but some turbine stages had to be replaced and new, rather than reworked, turbine guide vanes were required. In passing, it is interesting to note that the airlines invested in automated equipment not required for normal maintenance in order to complete the retrofit program.

The second airline reported that the time between hot section overhauls was reduced from 8500 hours to 5000 hours and the cost of an engine shop visit increased by 25%. It was also necessary to add a fuel nozzle cleaning program (with the engine on the wing) at a frequency of 1000 to 2000 hours.

JT 3D Smoke Program

The JT 3D smoke program was initiated in 1974 and is still in progress. A total of 26 sets of reduced smoke burners were released to seven airlines for evaluation. As of 10/14/77, the high time set had accumulated 7789 hours and the 26 sets had accumulated 150,669 hours, an average of 5800 hours per set. As the test progressed, problems were identified. Some burning and cracking in the burner clamp heatshield, the edges of the outer burner liner, and adjacent to the crossover tubes were detected. These problems were corrected by adding and rearranging cooling holes in the clamp, clamp heatshield, combustion chamber outlet duct, and the outer rear liner areas. Four sets of the new configuration were released to four airlines in February 1977. High time on these new sets through mid-October was 1285 hours.

JT 9D Modifications

The introduction of the JT 9D engine into commercial service was accelerated because of the immediate success of the B 747 program. The attendant engine durability problems resulted in substantial losses to Pratt and Whitney; their 1971 annual report shows a special provision in the amount of $137 million to cover the anticipated costs associated with correcting the problems. The modifications led first to the -3A and ultimately to the -7 version of the engine. The following account of -7 combustor development, taken from a 7/7/77 letter from G. N. Frazer, Vice President, Engineering, Pratt and Whitney to John DeKany, Mobile Source Air Pollution Control Programs, EPA, illustrates the dangers of truncated service tests.

The first durability problems occurred with a non-structural heatshield design to protect combustor sidewalls in the area of the combustion zone. New materials were used for the heatshield, and an endurance test of 2500 cycles was concluded on this configuration (Mod 2). The engineering change was released to production in 1972, 17 months after fault detection. The welding technique for bonding the heatshield to the combustor could not be used for production so the engineering change was withdrawn.

Meanwhile, the original (Mod 1) burner was found to cause severe turbine erosion through carbon buildup in the combustor. A cylindrical ring was designed to prevent carbon formation near the swirler skirt. Soft tooling was used to fabricate a combustor (Mod 2.5) for service test in August 1973. This Mod reduced carbon formation, but did not solve the heatshield problem. Eight months elapsed between the identification of the turbine erosion process and the release of Mod 2.5 to service test.

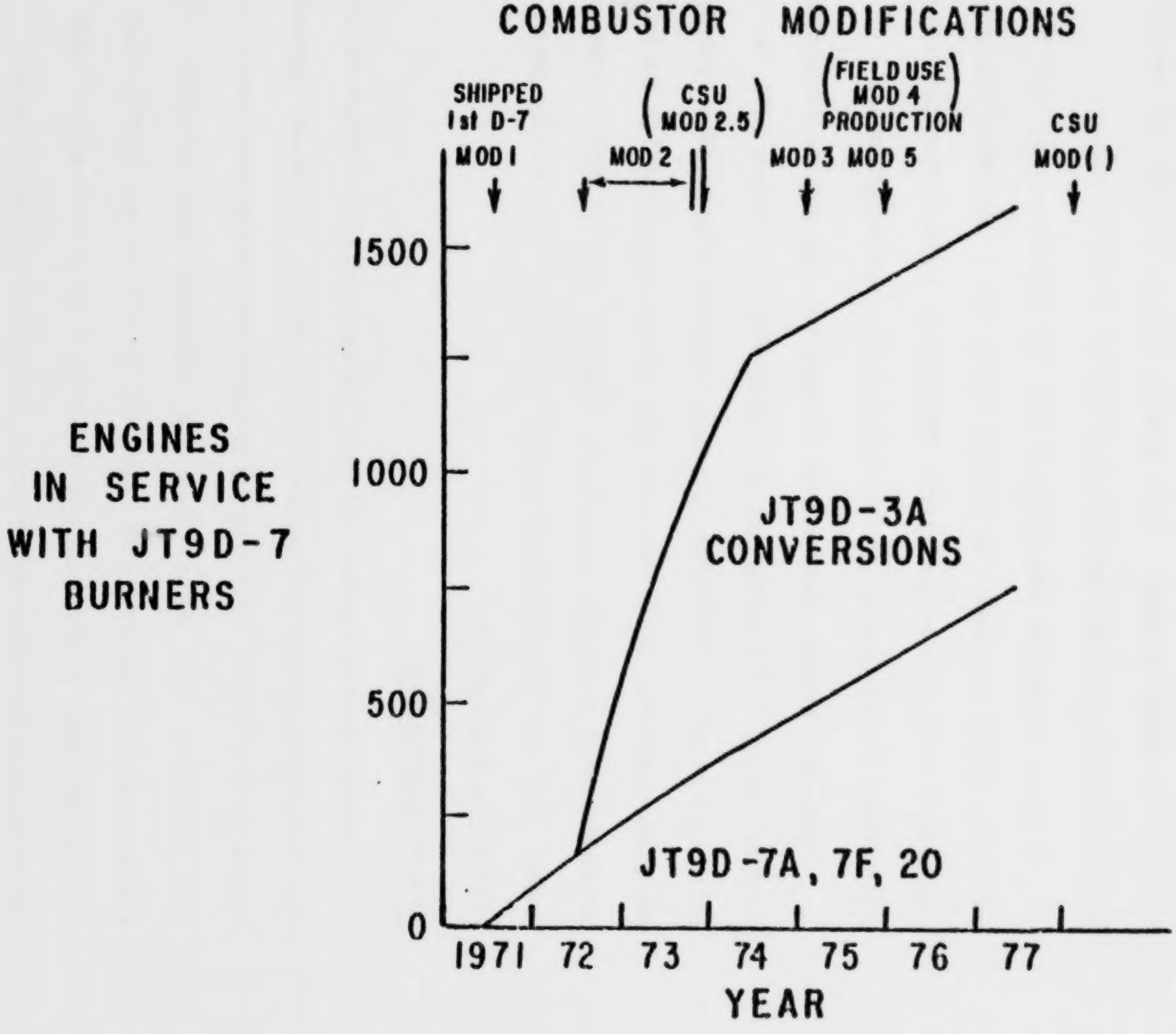
A Mod 3 combustor was designed with the cylindrical ring and the new material heatshield welded in place. In October 1974, Mod 3 combustors fabricated with soft tooling were ready for service testing. This was 23 months after the erosion problem was detected and 40 months after the heatshield faults were recognized.

Pratt and Whitney decided not to wait for full service evaluation, but instead incorporated the Mod 3 burner into production engines in March 1975. By November, the 13th month of service evaluation, it became apparent that the Mod 3 burner did not solve the erosion problem. A fix was found, but all engines produced in the interim had to be retrofitted with a suitable combustor. Figure 7 is a schematic diagram showing the various Mods and the number of engines in service. This history shows how losses of $140 million could accrue.

CF 6-50 Modifications

General Electric supplied LMI with two examples of combustor engineering changes. The first, characterized as a state-of-the-art change, introduced improved fuel nozzles for the CF 6-50 engine. The program consumed two and one-half years, from March 1974 until November 1976, when production shipments were initiated. The new parts accumulated 2000 factory engine cycles and the service test, slightly more than one year, allowed test parts to accumulate a maximum of about 2000 engine hours. The program was initiated to correct nozzle structural failures and coking problems.

JT9D POST CERTIFICATION DEVELOPMENT HISTORY



Courtesy Pratt & Whitney

FIGURE 7

The second example, a moderate advance in technology, was the CF 6–50 ruggedized (rolled ring) combustor. The change was required to increase combustor service life so as to reduce high warranty and secondary damage costs to GE and satisfy customer demands for better reliability. The program, initiated in October 1973, is planned for five and one-half years with production release scheduled for June 1979. A one-year service evaluation is planned. Note that the problem to be solved is associated with carbon deposits, and the solution, rolled rings and swirler modification, seems similar to the Mod 2.5 combustor for the JT 9.

Potential Maintenance Problems

The producers and the airlines contacted by LMI believe that maintenance costs for these engines will increase because of the increased complexity of the combustion systems. The exact impacts are difficult to predict, but sector burning and the staged combustors are the largest unknowns. Sector burning will require a more complicated fuel management system, probably fuel purging to prevent coking and/or premature ignition in the unused sectors, and a fail-safe control system to insure that sector burning occurs only on the ground. Exit temperature profiles and patterns in the sector burning mode will be quite different from when all nozzles are in use. Maximum temperatures encountered at idle will, however, be much less than those encountered at full power. Based on this, the differences in exit temperature patterns may not be serious. It remains to be seen, however, if the short duration changes from hot to cold temperatures experienced by the turbine blades each revolution at idle will cause long-term fatigue problems.

Some of the potential maintenance problems associated with staged burners were discussed earlier and need not be enumerated here. It is more to the point to note that engine maintenance costs are a non-trivial percentage of total aircraft operating costs.

Based on 1976 CAB data, engine-maintenance-related total aircraft operating expenses were as follows (domestic trunks).

Aircraft	Cost Per Block Hour Engine	Cost Per Block Hour Total	Engine Maint. As a Percent of Total
B 747	$419.61	$2,924.65	14.3%
DC 10-10	269.83	1,962.84	13.8
L 1011	248.42	2,217.48	11.2
B 707/DC 8	102.67	1,334.14	7.7
B 727	77.82	1,040.17	7.5
DC 9-30	46.45	766.65	6.1
B 737-200	93.74	997.48	9.4

Engine maintenance costs for these aircraft total $486 million or 9.6% of aircraft operating expenses. Thus, even a small change in maintenance costs will represent a significant dollar increase in airline expenses.

SUMMARY OF MAJOR ISSUES

This discussion has touched on all the major areas of disagreement between the aircraft industry and EPA position relative to the draft NPRM. Before summarizing the issues, it may well to reiterate two earlier points. First, the NPRM is a proposal, not a final rule-making. Moreover, the emission standards and implementation dates were not casually established, but were based on EPA's assessment of the best data available and included industry input and comment. Second, LMI has reviewed the draft NPRM and industry submissions and has visited producers in an attempt to identify rather than resolve potential technological problems.

With these qualifications in mind, the major issues are:

- Emission Standards - Two of the three producers feel that the retention of the 1973 standards for HC and CO emission, coupled with the change in definition of idle power setting, have in fact produced a new, more stringent standard. Since these standards are defined as maximums, actual design goals will be much lower to allow for engine-to-engine variation. All three producers believe that some compromises in the standards established for NME 84 will be required because not all engines will be able to meet all standards.

- Status of Low NOx Technology - EPA schedules and cost estimates seem to assume that the NASA PRTP and ECCP programs have demonstrated the required low NOx technology. U.S. producers disagree and believe that considerable development is required before prototype components and engines can be produced and tested.
- Requirements for Service Test - While it is difficult to determine the length of time allowed in the NPRM schedule for service testing, the document does state that EPA regarded industry's proposed development schedules as very conservative. It seems to LMI that the key issue is the length of time required for service evaluation. The complexity of the changes required for low NOx are significantly greater than the changes made in the examples cited above.

Other issues center around or are combinations of these. The producers stress commercially acceptable engines, as do the airlines. The producers also cite almost certain increases in engine maintenance costs. Chapter III attempts to quantify the impact of the technological issues just discussed on engine producers' and airlines' costs.

III. THE COSTS OF COMPLIANCE AND THEIR ECONOMIC IMPACT

CONTEXT OF THE ANALYSIS

This chapter presents the results of LMI's cost analysis, first in summary form and then in sequence, describing the current status of the air transport industry, the development of the base case and the costs of compliance and the use of the LMI Airline Economics Model to estimate the economic impact of the proposed EPA regulations. It should be stated at the outset that a considerable degree of uncertainty is associated with both the base case projections and the estimated costs of compliance.

The airline industry is in a period of transition from over-capacity and economic depression to an apparent resurgence of growth. Its fleet contains obsolescent aircraft, many of which do not meet recently promulgated noise abatement standards. Moreover, the Civil Aeronautics Board (CAB) is considering several proposals for what has been termed regulatory reform. It is possible, therefore, that the basic ground rules of the industry will be changing.

LMI had to rely on producers' cost estimates to develop the capital and operating cost increments associated with the proposed emission standards. No suitable parametric cost-estimating model for engines was available to us. Several well documented models exist, but these are useful only for estimating the development and/or production costs of new core engines. Moreover, the parameters required for these models (thrust, engine weight and other similar measures) are not applicable to this analysis. Thus there was really no alternative to accepting the inputs from producers and modifying them as judgment dictated.

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Sensitivity analyses were used to examine the implications of estimating errors for study results. This was done by varying each of the key parameters in the LMI Airline Economics Model individually and noting the results. The sensitivity analyses showed that wide variation in estimated air transportation demand had only a minor influence on economic impact. On the other hand, changes in economic impact were almost directly proportional to changes in costs of compliance incurred by the airlines.

The reasonableness of LMI's unit cost of compliance estimates is important in judging the validity of our results. Costs associated with NME 84 standards present the major problem. The producers' estimates are high, but vary significantly and unsystematically. General Electric did not update its earlier estimate because, in its view, the situation had not changed enough to warrant a new estimate. Both Pratt and Whitney and Rolls–Royce went through pricing exercises using internal measures of rate of return and sales projections to develop engine price increments including the recoupment of development costs. GE estimated NME 84 development costs in the range of $74-$92 million for the CF 6 family, while P&W estimated $116 million for the JT 9, a difference approaching 40%. The Rolls-Royce estimate for the RB 211 fell somewhere between these two, but is not typical of U.S. experience.

LMI believes that P&W generally takes a conservative approach to estimating engine costs and development time. Conversely, GE seems to have based its cost estimates on a 100% success program, which rarely happens. This discrepancy suggests that the best estimate of development costs for this class of engine lies somewhere between the two estimates.

The technology required for low emission combustors is considerably different from that now used. The engine producers have enumerated a number of difficult problems that remain to be solved. The reasonableness of the $100 million cost-to-complete estimate remains to be demonstrated, however.

A new core engine costs about $1 billion to develop at today's prices. The JT 10D, being developed by P&W and a consortium of foreign producers, provides one current example. The partners in the JT 10D program are committed to a $500 million investment on a share basis to carry the program through engine certification. Since at least as much development cost is expended after certification as before, the total development bill for the JT 10D will approximate the $1 billion rule-of-thumb.

The NME 84 low emission engines are not, of course, new core engines. A significant advance in combustor technology is required. Moreover, it is quite possible that the turbine section of the engines will require modification to accommodate burner output changes, or that air balance problems affecting the total engine will occur. It therefore does not seem inconsistent to assume that combustor development costs will approximate one-tenth of new engine development costs.

Pratt and Whitney has reported that the development and certification costs for the JT 8D-209 will be more than $100 million. The engine is essentially an improved version of the JT 8D-109, which was developed and flown on a DC 9 aircraft in a NASA-sponsored program. The -209 uses as many parts as practical from other JT 8D versions to take advantage of their service experience and maturity. These parts include the high pressure turbine, the combustor, gearbox, and fuel control system. The -109 fan will be used along with the low pressure compressor used on the Swedish RM 8 engine, a JT 8D derivative used on the Viggen fighter. The low pressure turbine is of advanced design based on JT 9 technology. It does not appear from this description that the technology of the JT 8D-209 development program is more advanced than that needed for low NOx engines.

SUMMARY OF RESULTS

The major results of the analysis in millions of 1978 dollars or percent of economic impact, as appropriate, are as follows:

Cost of Compliance (1981-1988)	Total	U.S.	Foreign
NME 81	$136	$ 69	$ 67
NME 84	825	448	377
IUE 85	573	386	187
Potential Penalties (1981-1988)			
Service Test (NME 81/IUE 85)	281	171	110
(NME 84)	494	267	227
Combustor Durability (NME 84)	569	336	233
Premature Engine Removal (IUE 85)	7	5	2

Economic Impacts

Engine Prices - NME 81: 1.53%; NME 84: 11-17%
Aircraft Prices - NME 81: 0.3-.5%; NME 84: 1.6-3.2%
Airline Fares - 0.20 to 0.77%
Demand Decrease - 0.34 to 0.54%
Airline Profits Increase - 2%
Increased Capital - Gross - 2.7%
- Outside - 14%

Airline Employment Decrease - 0.30 to 0.48%

The cost of compliance for U.S. airlines will range between $0.9 and $1.6 billion over the 1981-1988 period. This will produce minor impacts on airline fares, profits, and employment and will increase outside capital requirements by 14%. The magnitude of the potential penalties, $742 million, suggests a careful review of the technological issues discussed in Chapter II.

STATUS OF THE AIR TRANSPORT INDUSTRY

The three major components of the air transportation industry of interest in this analysis are airlines, aircraft manufacturers, and engine producers. Prospects for all three appear bright, but there are uncertainties. The market for new aircraft and new engines should be strong well into the 1980's, given the age of the existing fleet and the growing demand for air transportation. On the other hand, it is not clear what type of aircraft the airlines want or how new purchases can be financed. Moreover, while U.S.

airlines have traditionally decided what new designs would be produced by placing the critical first or launching orders, foreign, particularly European, airlines are becoming a more decisive factor in the air transport industry. The U.S. carriers' share of world traffic has declined from 56% to 46% of the total over the last 10 years, and foreign growth is expected to exceed U.S. domestic growth into the 1980's.

Airlines

Airlines can be characterized as both capital- and energy-intensive. Their capital intensiveness results in high fixed costs and a high level of operating leverage, that is, large funded debt as compared to net internal funds. Normally, companies with high leverage balance their business risks by reducing financial risk through conservatively constructed balance sheets. The airlines have not followed this practice, primarily because the risks associated with high leverage are more than offset by the regulated environment of the industry. Airlines have traditionally had a low level of competitive risk and assured route structures and fares.

This high leverage was not a problem during the 1960's, which was a period of substantial growth when the airlines used long-term loans from insurance companies and shorter-term loans from banks to finance the first round of jet transport orders. Growth tapered off in the early 1970's with the energy crisis and its resulting price increases, which reduced the economic efficiency of many aircraft in the fleet. The airlines also bought more capacity than they needed. The low point was 1975, when domestic traffic remained essentially the same as in 1974, international traffic actually declined, and losses for the industry totaled more than $100 million.

In 1976 and 1977, air traffic increased at a rate parallel to that of the 1960's. Profits were substantial in both years, but return on investment remained at less than regulated levels. Fuel consumption was actually reduced through less frequent flights and more fuel-efficient operating procedures. Load factors (percent of passengers to seats available) were increased. Prospects for continued growth in traffic seem reasonably good.

Yet, even with these prospects, the financing of new aircraft is problematical. The debt-equity ratio for trunks as a group was 1.75 at the end of 1976—with leased aircraft valued as equivalent debt. Many lenders consider this too high and would prefer a ratio of 1.5. If regulatory reform increases competition and opens route structures to new participants, many lenders will want a debt-equity ratio no higher than 1.[1] The airlines would have to reduce debt or increase equity by about $4 billion to achieve this ratio. Also, many analysts believe that the industry will require between $5 and $9 billion by 1984 for fleet expansion and modernization. These conditions indicate the existence of a serious financial problem.

There has been extensive public debate about regulatory reform, but as yet no explicit policy has evolved. CAB has indicated a change in philosophy, emphasizing more competition and lower fares. It has, moreover, recognized the impact of escalating costs on airline profitability by adopting an anticipatory cost concept in fare determinations. This should ease the gap between cost and price increases that accounted, in part, for the large losses in 1975.

The airline industry is by no means monolithic. Some trunk airlines are quite profitable and earn an impressive return on investment. Others, particularly Pan American and TWA, which have substantial international operations, have been consistent losers in recent years. Moreover, local service airlines are heavily subsidized ($60 million in 1975 and $74 million in 1976). All cargo and supplemental carriers have experienced mixed results.

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[1] Much of the information in this section is based on an address made by F. W. Bradley, Vice President, Aircraft and Aerospace Investment, Citibank Corp. as reported in Aviation Week for May 23, and July 11, 1977.

The trunk airlines, clearly the most important segment of the industry, have become more cost-conscious and are approaching fleet modernization with caution. Those companies able to procure new aircraft are selecting off-the-shelf-aircraft that best meet their individual route structures. Although they all recognize that new aircraft are desirable, none has been willing to commit itself to a major new aircraft.

The financial situation of the airlines has affected both engine and aircraft producers since the airlines have not agreed on design specifics for a new aircraft. Many key airline executives emphasize that an airline can no longer afford an all-purpose aircraft, but desire only a payload range capability that is more nearly energy- and cost-optimal for its route structure. The added front-end investment for spare parts and support equipment is a further deterrent to new aircraft acquisition.

Aircraft Manufacturers

The three major U.S. aircraft producers vary in terms of economic health and approach to the new aircraft market. Boeing plans to increase both production and employment in 1978. Production of the B 727-200, considered the star of the present group of Boeing aircraft, will be increased to 11 aircraft per month for 1978. McDonnell-Douglas has solid prospects with its DC 9 and DC 10 models. Lockheed, after a disappointing year, expects to produce enough L 1011 aircraft next year to exceed the breakeven point quoted as 18 aircraft per year. Commercial aircraft production and orders on hand as of 12/31/76 are shown in Table 1.

Boeing, which has not announced a new aircraft since the B 747 in 1966, is making a strong effort to sell an all-new aircraft (7X7 or 7N7). The contradictory desires expressed by the airlines have prevented a formal announcement in 1977, but design work continues and a family of highly common models is possible. At the same time, Boeing is offering a variety of B 747 derivatives, both larger and smaller and with longer or shorter ranges. Growth versions of the B 737 are also being studied.

TABLE 1. COMMERCIAL AIRCRAFT PRODUCTION 1970-1976

	Production							Orders-12/31/76		
	1970	1971	1972	1973	1974	1975	1976	Total	U.S.	Foreign
Wide Body										
4 Engine										
B 747	92	69	30	28	21	20	27	22	2	20
3 Engine										
DC 10	0	13	52	57	46	43	19	27	3	24
L 1011	0	0	17	39	41	25	16	70	38	32
Total	0	13	69	96	87	68	35	97	41	56
Regular Body										
4 Engine										
B 707	19	10	3	11	21	7	3	5	0	5
DC 8	33	13	4	0	0	0	0	0	0	0
Total	52	23	7	11	21	7	3	5	0	5
3 Engine										
B 727	54	33	41	92	91	91	61	106	93	13
2 Engine										
B 737	37	29	22	17	41	51	41	22	10	12
DC 9	51	43	24	21	48	35	44	47	17	30
Total	88	72	46	38	89	86	85	69	27	42
Fleet	286	210	193	265	309	273	211	299	163	136

Source: Aerospace Facts and Figures, 1977/1978

McDonnell-Douglas and Lockheed are both concentrating on derivative aircraft. Both believe that development cost is a barrier and that an all-new aircraft cannot be ready in time to meet early 1980's requirements. McDonnell-Douglas has already announced the DC 9-80, a super-stretched DC 9 derivative. Significantly, the launching orders for the aircraft were dominated by European airlines.

Engine Producers

The two major U.S. producers of commercial aircraft engines are also reasonably healthy. Jet engine production figures for 1970-1975 are shown in Table 2. General Electric is developing the CFM 56 and CF 34 engines, but as yet has no application for either. Boeing will construct and certify a B 707 aircraft with the CFM 56. One airline, Lufthansa, has expressed interest in such an aircraft for its international routes where traffic density does not justify use of a wide body aircraft. The engine could also be used to refan existing B 707 or DC 8 aircraft. Many of the DC 8's have an extended airframe life expectancy, so such a program is possible.[2] Moreover, the CFM 56, perhaps derated, could be used on derivatives of present two-engine aircraft such as the DC 9 or B 737. Its

TABLE 2. COMMERCIAL JET ENGINE PRODUCTION 1970-1975

	CF 6	JT 3D	JT 8D	JT 9D
1970	0	127	448	466
1971	119	49	176	369
1972	122	13	282	148
1973	162	74	469	164
1974	210	120	600	106
1975	132	21	542	159

Source: Aerospace Facts and Figures, 1976/77 use on B 727 derivatives would require a significant degree of airframe modification because of the center-mounted engine on that aircraft. The CF 34, rated at about 8000 pounds, seems more suitable for business jets than for the commercial aircraft treated in this study.

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[2] Note that the FAA fleet projections, discussed later in this chapter, include a significant number of the four-engine aircraft in the fleet as late as 1989.

Pratt and Whitney can expect continued sales of both the JT 9D and JT 8D families of engines. The JT 8D-209, a refanned version of the basic engine, will be used on the DC 9-80 aircraft and is a viable candidate for the reengining of both B 707 and DC 8 aircraft. It has a high degree of commonality with other 8D models, which are used by every scheduled U.S. airline. Thus, a growth version of the JT 8D-209 would be an attractive competitor to the CFM 56 in some applications, despite its greater weight and lower fuel efficiency.[3] Pratt and Whitney is also developing the JT 10D, a 30,000 pound thrust engine primarily for new aircraft application. The JT 10D is well suited to the 180-200 seat regular body aircraft favored by United Airlines, a key airline in the new aircraft market.

Rolls-Royce, the only foreign producer of commercial aircraft engines, expects to sell both RB 211 and Spey engines for aircraft operated in the U.S. The M 45, developed for the now defunct VFW 614 transport, is more suited to business jet applications than to the aircraft considered here.

All three producers are planning (or developing) "clipped fan" or derated versions of their large engines (CF 6, JT 9D, RB 211). These engines are likely to be suitable for any wide body aircraft derivative likely to be considered by the aircraft producers.

The future of the air transport industry remains uncertain. Although air traffic can be expected to increase, and with it the demand for new aircraft and engines, it is not clear how these purchases will be financed. U.S. aircraft producers are generally concentrating on derivatives of existing designs and engine manufacturers are developing a few new engines suitable primarily for regular body aircraft. There are likely to be few, if any, all-new aircraft or new core engines until the late 1980's, except for those already planned.

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[3] This judgment excludes environmental considerations. The CFM 56 is both quieter and cleaner than the JT 8D-209.

DEVELOPING THE BASE CASE

Despite the uncertainties just described, it is necessary to project a fleet of aircraft in order to develop the cost of compliance with the proposed EPA standards. LMI relied on the best available forecasts to obtain control totals of aircraft in the fleet. These forecasts were made in terms of aircraft generic type as shown in Table 3. No attempt was made to forecast inventories or deliveries of specific engine types, primarily because the CF 6, RB 211 and JT 9D can each be used on all versions of wide body aircraft. Instead, unit costs of compliance for each type of aircraft were estimated from producer and airline cost inputs.

TABLE 3. AIRCRAFT IN EACH GENERIC CATEGORY

4 Engine Wide Body (4EWB)	B 747
3 Engine Wide Body (3EWB)	DC 10, L 1011
2 Engine Wide Body (2EWB)	A 300, A 200
4 Engine Regular Body (4ERB)	B 707, B 720, DC 8, CV 990 COMET, VC 10
3 Engine Regular Body (3ERB)	B 727, HS 121 Trident
2 Engine Regular Body (2ERB)	B 737, DC 9, BAC 111, F 28 Mercure, Caravelle, VFW 614

The base case is an estimate of air transportation activity and commercial results assuming no impact from gaseous emission standards. The best available forecasts of demand (passengers, passenger miles), and supply (fleet, available seat miles) are the annual projections proposed routinely by the Federal Aviation Administration.[4] These forecasts are integrated, hence internally consistent. The fleet projected for each year is capable of generating the required seat miles, and the enplaned passengers, traveling a reasonable trip distance, will generate the predicted passenger miles. Other factors, such as aircraft operations and aircraft flight hours, are similarly consistent.

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[4] The 1976 forecasts, titled Aviation Forecasts, Fiscal Years 1977-88, FAA AVP-76-17, were published in September 1976. FAA supplied advanced copies of pertinent 1977 forecasts for use in this study. Publication was expected in December 1977.

Demand Forecasts

FAA forecasts continued growth for the airlines, with passenger miles increasing approximately 5% per year through 1989. Passenger miles in 1989 are projected as 359 billion for scheduled service by certificated carriers, or about 90% more than the fiscal year 1977 estimate, 186 billion. Similarly, passengers boarded will increase from 232 million in 1977 to 418 million in 1989. Year-by-year totals are shown in Table 4.

TABLE 4. FAA FORECAST OF TRAFFIC DEMAND
SCHEDULED PASSENGER SERVICE
U.S. CERTIFICATED CARRIERS

Year	Enplaned Passengers (Millions) Total	Domestic	International	Passenger Miles (Billions) Total	Domestic	International
1978	248.1	229.1	19.0	200.1	162.2	37.9
1979	263.2	242.9	20.3	213.3	172.7	40.6
1980	274.2	253.0	21.2	223.3	180.9	42.4
1981	286.3	264.1	22.2	234.5	189.9	44.6
1982	303.4	279.7	23.7	250.1	202.2	47.9
1983	320.2	294.9	25.3	265.6	214.4	51.2
1984	336.3	309.7	26.6	280.5	226.4	54.1
1985	351.7	323.7	28.0	294.9	237.9	57.0
1986	367.0	337.6	29.4	309.9	249.8	60.1
1987	383.4	352.6	30.8	325.6	262.3	63.3
1988	400.6	368.2	32.4	342.2	275.4	66.8
1989	418.4	384.4	34.0	359.3	289.1	70.2

The FAA forecasts are for scheduled service only and do not include all commercial operators. Supplemental airlines operate unscheduled service, and intrastate carriers such as Pacific South West, Air California, Southwest, and Air Florida are not defined as certificated carriers. Table 5 shows actual traffic for the 12-month period ending 30 June 1977. The certificated carriers enplaned 237 million passengers and generated 206 billion

TABLE 5. STATISTICS FOR CERTIFICATED CARRIERS 12 MONTHS ENDING 6/30/77

	Available Seat Miles (Billions)		Revenue Passenger Miles (Billions)		Enplaned Passengers (Millions)		Load Factor	
	Sched	Unsched	Sched	Unsched	Sched	Unsched	Sched	Unsched
Domestic Trunks	243.4	7.4	134.6	5.9	164.6	2.7	55.3%	79.4%
Local Service	24.0	1.0	12.7	0.6	39.5	0.7	52.8	64.9
International Trunks	62.7	6.6	34.8	5.9	17.3	1.7	55.4	89.1
Alaska	1.5	(a)	0.9	(a)	1.5	0.1	60.1	46.4
Hawaii	1.1	(a)	0.7	(a)	5.5	(b)	64.6	92.0
All Cargo	0	0.7	0	0.7	0	0.1	0	97.4
Other	0.2	(a)	0.1	(a)	1.0	0.1	50.0	52.9
Supplementals	0	10.5	0	9.3	0	2.6	0	88.8
Total	348.9	26.3	183.8	22.4	229.4	8.0	55.2%	85.4%

(a) Less than 50 million; (b) Less than 50,000 passenger miles during the period. Of this, 8 million passengers and 22 billion passenger miles were from unscheduled services. The non-certificated intrastate carriers produced an estimated additional 4 to 5 billion passenger miles. In comparison to these totals, the FAA projections of passengers and passenger miles understate total activity by about 10% for passengers and 15% for passenger miles.

The demand projections are the key element in determining costs of compliance and economic impact. Projected passengers and passenger miles are the driving variables in determining airline revenues, expenses, profits and capital requirements. The projected fleet, with proper time-phased additions and retirements, provides the basis for determining the number of engines affected by each part of the regulation. Under these circumstances, some assessment of the FAA projections is advisable.

Passengers and passenger miles for the period 1966-76 are shown in Table 6. The table shows that overall traffic increased about 12% per year between 1966 and 1969, about 5% per year for 1970 to 1973, and remained relatively constant for 1973, 1974 and 1975. However, with the large increase in 1976, the average traffic increase was more than 6% per year for 1970 to 1977. The traffic increase for the entire period, 1966–76, was 140%, or an average of more than 9% per year. These figures indicate that the substantial growth predicted by FAA has some historical foundation.

Aircraft and Engine Forecasts[5]

The FAA fleet projection is shown in Table 7 where the totals represent inventories as of January 1 of each year. Inventories alone, however, do not allow derivation of the number of engines affected by the three major provisions of the NPRM. It is also necessary to consider additions to and retirements from the fleet. LMI used information contained in a recent EPA cost-effectiveness study[6] and the results of an Air Transportation Association survey to estimate the number of new aircraft to be added to

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[5] A more detailed discussion of the fleet forecasts and the number of engines affected by each section of the proposed regulation is contained in Appendix A.

TABLE 6. PASSENGERS AND PASSENGER MILES - CERTIFICATED CARRIERS 1966-1976

	Passengers (Millions)				
	Domestic Trunks	Local Service	Inter-National	Other	Total
1966	85.4	16.3	12.3	4.1	118.1
1967	105.9	19.0	14.0	3.6	142.5
1968	118.8	23.4	16.4	3.6	162.2
1969	129.9	24.5	13.5	4.0	171.9
1970	122.7	26.7	16.3	4.2	169.9
1971	124.4	27.4	17.5	4.4	173.7
1972	136.6	30.5	18.9	5.3	191.3
1973	144.8	32.5	18.9	6.0	202.2
1974	148.0	35.2	17.7	6.6	207.5
1975	147.4	34.4	16.3	7.0	205.1
1976	163.0	39.0	18.7	7.8	228.5
	Passenger Miles (Billions)				
1966	56.8	3.5	19.3	0.3	79.9
1967	71.0	4.1	23.2	0.4	98.7
1968	81.6	5.5	26.5	0.8	114.0
1969	95.7	6.3	22.7	0.7	125.4
1970	95.9	7.4	27.6	0.8	131.7
1971	97.8	7.9	29.2	0.8	135.7
1972	108.2	8.9	34.3	1.0	152.4
1973	115.4	9.8	35.6	1.2	162.0
1974	117.6	10.8	33.2	1.3	162.9
1975	119.4	10.7	31.1	1.6	162.8
1976	137.0	12.7	39.6	2.5	191.8

Source: Air Transportation, 1977

the fleet. These figures were then grouped according to the three regulatory categories of the NPRM, as shown in Table 8.

TABLE 7. FAA ESTIMATE OF THE U.S. AIR CARRIER FLEET AS OF JANUARY 1

Jet Aircraft Only

	1977	1980	1985	1989
Standard Body				
4 Engine Passenger	399	357	146	131
4 Engine Cargo	88	80	56	51
Total	487	437	202	182
3 Engine Passenger	823	923	913	840
2 Engine Passenger	536	631	825	840
Wide Body				
4 Engine Passenger	94	119	209	255
4 Engine Cargo	12	19	32	37
Total	106	128	241	292
3 Engine Passenger	202	230	450	645
3 Engine Cargo	0	2	13	16
Total	202	232	463	661
2 Engine Passenger	0	32	135	239
Total Fleet	2154	2393	2779	3054

The proposed regulation will require all aircraft operating to or from U.S. airports to meet the emission standards. Some of these aircraft will be foreign; therefore some projections of the foreign fleet must be made. LMI developed gross estimates based on two assumptions. First, substantial growth in foreign traffic can be expected during the

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[6] R. S. Wilcox and R. Munt, Cost-Effectiveness Analysis of the Proposed Revision in the Exhaust Emission Standards for New and In-Use Gas Turbine Engines Based on Industry Submittals, EPA Draft Report AC 77-02, November 1977.

TABLE 8. AIRCRAFT BY REGULATORY CLASS

	NME 81	NME 84	IUE 85
Wide Body			
4 Engine	66	81	145
3 Engine	145	244	272
2 Engine	62	125	52
Regular Body			
4 Engine	0	0	202
3 Engine	58	41	839
2 Engine	150	109	650
Total	481	600	2160

Notes: NME 81 represents the aircraft purchased between 1981 and 1983 subject to the 1981 HC/CO standard.

NME 84 represents the aircraft purchased between 1984 and 1988 subject to the 1984 NOx standard.

IUE 85 represents the aircraft in the inventory at the end of 1984 subject to the in-use engine HC/CO standard effective 1/1/85.

1980's. Second, because the composition of the foreign and U.S. fleets as of 12/31/76 is known, the ratio of foreign to U.S. aircraft in each category in 1976 can be used to estimate foreign procurements as a percentage of U.S. procurements. Table 9 shows the foreign and U.S. fleets as of the end of 1976.

The percentages shown in Table 9 are most useful for the three- and four-engine wide body (3EWB and 4EWB) aircraft, since these classes of aircraft are all U.S.-produced and are limited to the Boeing 747, McDonnell-Douglas DC 10, and the Lockheed L 1011. These models can be expected to be efficient throughout the 1980's and no all-new designs are expected until the late 1980's at the earliest.

TABLE 9. FOREIGN AND U.S. FLEETS 12/31/76

	Fleets U.S.	Fleets Foreign	Foreign as a % of U.S.
Wide Body			
4 Engine	105	163	155%
3 Engine	202	142	70
2 Engine	0	24	-
Regular Body			
4 Engine	476	786	165%
3 Engine	820	451	55
2 Engine	535	1106	207
Total	2138	2672	125%

Source: Aviation Facts and Figures 1977/78, Aerospace Industry Association

The only available 2EWB aircraft is the French-German Airbus A 300. Boeing may enter this market, but neither Lockheed nor McDonnell-Douglas is now considering any all-new aircraft of this type. Both are concentrating on derivatives of present designs. The FAA projections include a large fleet of 2EWB aircraft in the U.S. by 1989 and we assume that the same number will be procured by foreign operators. Since few of the foreign aircraft will operate in the U.S., it seems unlikely that the engines used on them will necessarily meet the 1984 NOx standards.

Regular body aircraft require careful consideration. One four-engine regular body aircraft (4ERB), the B 707, is still in limited production for the foreign market. Although Lufthansa has expressed interest in a reengined B 707 for its less dense international traffic routes, no new 4ERB aircraft have been included in the projections.

The 3ERB aircraft (B 727 and BAC Tridents) has been more popular with U.S. airlines than with foreign ones. The B 727 and Trident represent only 17% of the foreign fleet. In addition, the recently announced DC 9-80, undertaken on the basis of European orders, is a direct competitor of the B 727, and a large number of used B 727's will be coming on the market in the 1980's. Moreover, only a few foreign 3ERB aircraft will operate in the U.S., primarily those used by North and Central American operators. For these reasons, LMI estimates that new 3ERB aircraft in the foreign fleet subject to the EPA regulations will amount to only about 15% of U.S. procurements.

The 2ERB aircraft, which total 25% of the U.S. fleet, amount to about 40% of the foreign fleet. Besides the U.S.-produced B 737 and DC 9, the foreign fleet includes a large number of foreign-produced BAC 111, Caravelle and Fokker F 28 aircraft, few of which operate to U.S. points. A number of aircraft in this category, operated by Canadian, Mexican, and Caribbean airlines, have regular routes to many U.S. cities. LMI estimates that the number of new foreign aircraft in the 2ERB category subject to regulation will be about 60% of the U.S. total.

TABLE 10. TOTAL ENGINES IN EACH CATEGORY

	U.S.	Foreign	Total
NME 81			
Wide Body			
4 Engine	330	495	825
3 Engine	540	380	920
2 Engine	155	155	310
Regular Body			
3 Engine	210	30	240
2 Engine	360	210	570
NME 84			
Wide Body			
4 Engine	405	605	1010
3 Engine	915	640	1555
2 Engine	310	310	620
Regular Body			
3 Engine	145	20	165
2 Engine	260	150	410
IUE 85			
Wide Body			
4 Engine	725	875	1600
3 Engine	1020	350	1370
2 Engine	130	0	130
Regular Body			
3 Engine	3020	180	3200
2 Engine	1560	240	1800

Table 10 shows total (U.S. and foreign) engines required to support the number of aircraft projected for each regulatory category. The totals include an allowance for spare engines based on the normal stockage policy of several airlines.

DEVELOPING THE COSTS OF COMPLIANCE

Production Costs

Unit costs of compliance, that is, cost per engine, are shown in Table 11. The entries, expressed in 1978 dollars, represent price increments or increased costs to users of the engine. These include: amortized development costs and preproduction costs, such as tooling and manufacturing cost increases.

TABLE 11. UNIT COSTS OF COMPLIANCE
(Thousands of Dollars)

	NME 81	NME 84	IUE 85
Wide Body			
4 Engine	$50	$300	$150
3 Engine	40	200	110
2 Engine	40	200	110
Regular Body			
4 Engine	NA	NA	NA
3 Engine	$12	NA	$ 35
2 Engine	12	NA	35

The three large engines now in production (JT 9D, CF 6, RB 211) can be used on all of the wide body aircraft.[7] Lower average costs were used for two- and three-engine wide bodies to reflect the use of clipped fan versions of the engines on derivative aircraft.

No unit costs of compliance have been estimated for 4ERB aircraft. LMI does not believe that new four-engine aircraft will be produced in significant numbers and has therefore treated NME 81 or NME 84 as not applicable in this analysis.

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[7] No L 1011 aircraft use an engine other than the RB 211 at this time. Lockheed, in discussing L 1011 derivatives, is offering any of the three engines. This should make the aircraft more attractive to airlines who already have the CF 6 or JT 9 in their inventories.

The JT 3D engine which is used on most 4 ERB aircraft now in service is excluded from the IUE 85 requirement in the draft NPRM. The FAA projections include 202 of these aircraft as of 1/1/85 and 182 as of 1/1/89. These aircraft can meet the current noise standards by sound treatment of nacelles or by reengining. Nacelle treatment of the 4 ERB aircraft can be accomplished for about $2 million each;[8] reengining with a JT 8D-209 for about $7 million or with the CFM 56 for about $10 million including airframe modifications.[9] Fuel consumptions would be improved about 9% using the -209 and 13% using the CFM 56. Based on these estimates for DC 8 aircraft, the cost of reengining 200 aircraft would be approximately $1.5 billion, offset by a fuel saving of between $200 and $400 million through 1988.

There are also problems in estimating compliance costs for 2ERB and 3ERB aircraft. The latest Boeing aircraft discussed in the literature[10] is tending toward a family, i.e., twin and tri-jet versions using the same main body. The earliest decision date on a final design seems to be mid-1978. The aircraft may grow out of the regular body class and, in any event, thrust requirements appear greater than those available in the JT 8D-209, CFM 56, or as now planned, the JT 10D. Boeing is, however, considering a super-stretched B 737.

It does not appear probable to LMI that any all-new 2 or 3 ERB aircraft will be added to the inventory much before the NME 84 deadline. New aircraft and the engines to be used in the last half of the 1980's are not clear at this time. Both the JT 10D and CFM 56 are expected to be certified before the end of 1981 and both will meet NME 81 standards. Thus, if either of these is used, there will be no cost impact associated with

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[8] L. Davis, "Congress Reviewing Engine Retrofit Program," Aviation Week, September 1977.

[9] J. M. Lenorovitz, "Two New Engines Offered for DC 8", Aviation Week, May 16, 1977.

[10] Aviation Week, November 7, 1977.

NME 81 or IUE 85. Since no aircraft-engine combinations could be defined for the post-1984 period, LMI used the costs of meeting NME 81 for the entire period. This assumes that the engines used would be below the 20,000 pound thrust threshold established in the draft NPRM.[11] LMI could find no logical basis for using a different assumption.

Maintenance Costs

Maintenance costs could be expected to increase because of increased combustor complexity. Cost per engine will increase about 3.6% for wide body aircraft and about 0.6% for regular body aircraft as a result of NME 81. A 10% to 45% increase in wide body engine maintenance cost is associated with NME 84, depending on the combustor life achieved. Fuel consumption could be reduced because of more efficient combustion at idle. LMI has used the EPA estimate of a 5% saving at idle for wide body engines and a 1% saving for regular body engines to estimate total fuel saved. The NME 84 engine will, however, be heavier, and will therefore require more fuel to carry a given payload over a given route segment.

Other Costs

There are other possible cost penalties. As discussed in Chapter II, the proposed implementation dates may not allow producers to conduct adequate service tests before introducing the reduced emission engines into commercial use. LMI used information supplied by Pratt and Whitney to quantify these impacts. The estimates should be regarded as the maximum penalty that could be incurred if the schedule problems cited by the manufacturers occur. Information from the same source was used to estimate the penalties associated with combustor durability, a largely unknown factor at this stage of development.

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[11] Possible changes in the NME 84 NOx threshold have not been considered in this analysis.

Total Cost of Compliance

Table 12 shows the total cost of compliance (in 1978 dollars) associated with HC/CO and NOx reduction. Best and worst case totals are shown where the worst case includes the following penalties (millions):

	Total	U.S.	Foreign
Service Test			
HC/CO	$281	$171	$110
NOx	494	267	227
Combustor Durability			
NOx	$569	$336	$233
Premature Removal of Engines			
HC/CO	$ 7	$ 5	$ 2

TABLE 12. TOTAL COST OF COMPLIANCE 1981-1988 (Millions of Dollars)

	Total	U.S.	Foreign
Best Case			
NME 81	$ 136	$ 69	$ 67
IUE 85	573	386	187
Total HC/CO	$ 709	$ 455	$ 254
NOx Control	825	448	377
Total Program	$1,534	$ 903	$ 631
Worst Case			
NME 81	$ 272	$ 139	$ 133
IUE 85	724	492	232
Total HC/CO	$ 996	$ 631	$ 365
NOx Control	1,887	1,051	836
Total Program	$2,883	$1,682	$1,201

ESTIMATING THE ECONOMIC IMPACT

The costs of compliance and base case traffic projections were used as inputs to the LMI Airline Economics Model to estimate the following types of economic impact:

- Price/Fare Effects
- Demand for Air Transportation
- Airline Employment
- Airline Profits

Factors considered outside the model included

- Engine Prices
- Aircraft Prices
- Energy Consumption
- Balance of Trade

Airline capital requirements were considered both inside and outside the model.

The Airline Economics Model accepts traffic forecasts and time-phased pollution abatement costs as inputs. It first generates base case airline revenues, expenses, profits, capital requirements, return on investment, and debt-equity ratio. Next the model considers the year-by-year cost of pollution abatement. Capital costs are converted to annual costs (depreciation) and added to operating and maintenance cost penalties or gains. These cost increases are used to calculate the price increase required to allow the airlines to earn the same return on investment as in the base case. The price increase calculated includes consideration of demand-price elasticity, so that as price goes up, demand (enplaned passengers and passenger miles) goes down. The model has actually calculated all the factors in the base case and prints them out along with the differences (plus or minus) from the base case. Development of the model is fully described in an earlier LMI study of the economic impact of noise abatement procedures.[12]

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[12] C. F. Day and J. M. White, Economic Impacts of Alternative Airport Noise Abatement Programs, Logistics Management Institute, November 1976.

The Airline Economics Model is based on the assumption that the structure of the industry will remain essentially the same. It also assumes that allowable price increases will become effective at the same time cost increases occur. These assumptions, coupled with the monotonic increasing FAA projections of traffic, smooth out normal plateaus in traffic growth and profits and give a somewhat optimistic view of airline operations and business results. This lack of realism is not too serious in measuring economic impacts. The impacts are calculated by their deviation from the base case and sensitivity analysis confirms that the estimates are relatively insensitive to rather wide variations in demand.

The economic impacts associated with the reduction of gaseous emissions are relatively small. Compliance costs are only a small fraction of total airline revenue and expenses. In 1976, for example, trunk airlines generated 177 billion passenger miles, yielding revenues of $15.5 billion and expenses of $14.9 billion. When 1976 price and cost factors are applied to the FAA traffic projection, they show that the industry would generate $202 billion in revenues and incur $194 billion in expenses for 1981-1988. The $900 million bill for emission reduction incurred over the same period represents a cost increase of less than 0.5%.

Table 13 shows the economic impacts estimated from the model: fares, demand for travel, airline employment, and airline profits. All changes are less than 1%, except for profits, which would increase about 2%, reflecting the model's assumption concerning return on investment. Table 14 shows the impacts on engine and aircraft prices.

Energy consumption should be reduced marginally because of the estimated increase in engine combustion efficiency at idle. Engine manufacturers agree that there will be no improvements in specific fuel consumption at other power settings. Total fuel savings will be about 530 million gallons over the period. Note that the industry consumed more than 10.2 billion gallons for the 12 months ending 30 June 1977 indicating a fuel saving of less than one half of one percent for 1981-88.

TABLE 13. ECONOMIC IMPACTS FROM LMI AIRLINE ECONOMICS MODEL

1981-1988

	Percent Change
Airline Fares	
1981-1988 Range of Increases	0.20-0.77%
Maximum Increase - without penalties	0.62
- with penalties	0.95
Demand for Air Travel (passenger Miles)	
1981-1988 Range of Decreases	0.34-0.54%
Maximum Decrease - without penalties	0.45
- with penalties	0.54
Airline Employment	
1981-1988 Range of Decreases	0.29-0.48%
Maximum Decrease - without penalties	0.46
- with penalties	0.69
Airline Profits	
1981-1988 Range of Increases	2.10-3.06%
Maximum Increase - without penalty	3.06
- with penalty	3.06

TABLE 14. ENGINE AND AIRCRAFT PRICE INCREASES

(1978 Dollars in Millions)

Aircraft Type	Base Price		NME 81			NME 84		
			Price Increment	Price Increase %		Price Increment	Price Increase %	
	Engine	Aircraft		Engine	Aircraft		Engine	Aircraft
4EWB	$1.5 -$1.8	$36-$41	.050	2.8%	0.5%	$300	16.7%	3.2%
3EWB	1.5 - 1.8	30- 32	.040	2.3	0.4	200	11.4	1.9
2EWB	1.5 - 1.8	24- 26	.040	2.3	0.3	200	11.4	1.6
3ERB	0.75- 0.9	$11-$12.5	.012	1.5%	0.3%	NA	NA	NA
2ERB	0.75- 0.9	8- 9.5	.012	1.5	0.3	NA	NA	NA

Given the assumptions of this study, there should be no major impact on air-transportation-related balance of trade. The draft NPRM assumes, however, that all aircraft operating to U.S. points will meet the standards regardless of ownership. Operating rights are historically negotiated through bilateral agreements, and it is by no means certain that foreign carriers will be required to comply. If not, then U.S. engine producers and, perhaps aircraft producers, could be at a competitive disadvantage. This is an unlikely possibility, but in any event, quantification of any impact of negotiated operating rights on the balance of trade is clearly beyond the scope of this analysis.

Airline Capital Requirements

The impact on airline capital requirements, or more specifically their ability to attract outside capital is less easy to quantify. The FAA projections, as interpreted by LMI, require the addition of more than 1000 aircraft during the 1981-88 period at a cost of $27 billion. The Airline Economics Model, using the FAA traffic projections, has an implicit assumption of gross capital growth of $30 billion, based on an increase in capital (long-term debt plus stockholders' equity) of $11 billion and depreciation of $19 billion. The model predicts that about $24 billion dollars can be generated from internal sources with the remaining $6 billion being required from outside debt or equity. The additional capital required for pollution abatement is about $820 million or 2.7% of the total capital required. That this $820 million increases outside capital requirements by 14% is not necessarily serious, because the industry debt-equity ratio is predicted to be well under the 1:1 threshold cited in the literature. The model may, however, understate outside capital requirements because of the monotonic increasing traffic projections and the assumption of minimal regulatory lag.

A recent study by Shields Model Roland (SMR), reported in Aviation Week for July 11, 1977, tends to support LMI's results. The SMR study assumed that market shares would remain stable and that new credit would be available to airlines achieving a debt-equity ratio of 1. A simulation model was used in which outside borrowing was made a function of earning power. The prime measure of earning power used was the ratio of new investment in any year to net cash generated (net profit plus depreciation minus dividends). The study showed that if new investment on a year-to-year basis stayed below 175% of net cash generated, a carrier could maintain a reasonable debt-equity ratio and show stable profits. Under these conditions, three (Northwest, Delta, and United) of the eleven trunk airlines had investment capacities significantly greater than their needs, four (Braniff, National, Western, and Continental) had capacity marginally greater than their needs, and four (American, Pan American, TWA, and Eastern) had insufficient capacity. The total air transport industry had an excess investment capacity of some $12.6 billion for the period 1976-1990.

IV. REGULATORY IMPLICATIONS

The main purpose of this study was to develop estimates of the economic impact of the revised standards in the NPRM. Chapter III has shown that the costs of compliance, while large in themselves, are relatively small in comparison to projected airline revenues and expenses. However, as pointed out in Chapter II, given the present status of low emission technology, there may be other potential cost penalties attached to developing commercially acceptable engines in time to meet the proposed EPA standards. In this chapter, we turn our attention to some of the regulatory implications of the draft NPRM that our analysis of the costs of compliance has suggested.

WHAT CONSTITUTES COMMERCIAL USE?

The draft NPRM exempts non-commercial aircraft engines from the proposed standards. Yet it specifically defines only commercial engines:

> commercial aircraft engine means any aircraft engine used by an air carrier, foreign air carrier, supplemental air carrier, or charter air carrier, or charter air carrier engaging in: (1) interstate or overseas air transportation, (2) foreign air transportation, or (3) intrastate air transportation with large aircraft.

"Large aircraft" are not defined, and non-commercial aircraft engines are defined only by inference as other than commercial.

The revised definitions thus leave the matter of what engines are (or should be) covered by the regulation ambiguous. Perhaps this is inevitable since some engines are used as both general aviation and commercial aircraft (as defined by FAA) and some aircraft are used in both commercial and non-commercial service. Table 15 shows a listing of candidate turbine engines and the aircraft using them. Several of the engines are still in development and as yet have not been selected by an aircraft producer. The most important of these are the JT 10D and the CFM 56, both viable candidates for the next generation of aircraft.

TABLE 15. TURBINE ENGINES AND USING AIRCRAFT

Engine	Takeoff Thrust (Pounds)	Aircraft
JT 3D	17,000-19,000	B 707, DC 8
JT 8D	14,000-19,200	B 727, B 737, DC 9, Mercure
JT 9D	45,000-53,000	B 747, DC 10
JT 10D	25,000-35,000	NONE
CF 6	41,000-54,000	B 747, DC 10, A 300
CFM 54	22,000-25,000	NONE
CF 34	8,000	NONE
RB 211	42,000-55,000	L 1011, B 747
RR Spey	10,400-12,600	BAC 111, Gulfstream II, F 28, HS 121
M 45	7,600	VFW 614
RR Avon	11,400-12,200	Caravelle
501-D 22A*	11,700	L 100 (Commercial C 130)
501-D 13*	9,400	L 188 (Electra)

*Turboprop engines with equivalent thrust

The question of coverage is clear-cut for most of the engines. The Rolls-Royce Spey engine series presents problems on two counts. First it is used on both general aviation (Gulfstream II) and commercial aircraft. Second, some versions of the engine fall under the 12,000 pounds thrust criterion for IUE 85 while others are above. If the threshold was established to exempt the Spey, EPA may wish to eliminate this ambiguity.

Note also that Lockheed continues to produce the L 100/C 130 family of turboprop cargo aircraft and is proposing a two-engine version, the L 400. Most sales of the L 100 commercial versions are to foreign operators, although several have been sold to U.S. users over the past year. Production, if continued, will undoubtedly remain at a very low level and the possible operation of these aircraft at U.S. airports will not create an air pollution problem. LMI, therefore, did not consider the L 100 in the economic impact analysis.

The utilization of transport aircraft presents a much more difficult problem relative to EPA definitions. Aircraft have very long physical and economic lives. In fact, as a particular model becomes "uneconomic" for one class of user, it can be used profitably by another. Thus, aircraft phased out by trunk airlines can be sold to other users — foreign airlines, supplemental carriers or even corporate users. Some new transport aircraft are sold to non-commercial users although most such sales are exports and the number is small.

The predominant use of transport aircraft is clearly commercial, so all engines used on them should meet newly manufactured or newly certified standards. The retrofit requirement for in-use engines presents a more difficult problem. Corporate operators are not generally assumed to be "commercial operators" since they do not carry passengers or cargo for compensation. Many corporations operate a sizable fleet of jet aircraft as a supplement to commercial transportation, mostly small aircraft classified as business jets. The number of jet transports operated by corporate users is quite small at this time — perhaps 40 aircraft. More of this type of aircraft are being considered, however, and as older transports are phased out of airline operations for economic or noise pollution reasons, they may become attractive to corporate users. It seems possible, for example, that the cost of a refurbished DC 9 or B 737 in the early 1980's will be comparable to that of the top-of-the-line business jet.

EPA should consider whether the benefits derived from including these aircraft under the IUE 85 standard are sufficient to warrant the added administrative burden. The corporate aircraft will generally operate from the same airports as commercial aircraft. The number of flights per aircraft and total hours operated per year will, however, be only about 25% of airline usage in most cases. These aircraft were excluded from the economic impact analysis because the number of them flown by corporate users will be small in comparison to those flown by commercial users and because it is difficult to assess the potential economic impact on corporate users.

The major users of commercial jet engines in the U.S. are certified air carriers engaging in interstate commerce and intrastate carriers using commercial jet transports. Air taxi operators, who supply transportation on a for-hire basis, are also users insofar as they utilize commercial jet transports. More specifically, the users of commercial jet engines include:

- Domestic trunk airlines
- International trunk airlines
- Local service airlines
- All cargo airlines, domestic and international
- Supplemental air carriers, that is, those carriers certificated by CAB to provide unscheduled passenger and cargo service
- Foreign airlines providing scheduled service to the U.S.
- Foreign operators providing unscheduled service to the U.S.
- Corporate and air taxi operators using commercial jet transports

Except possibly for the Spey engine, the engines covered by NME 81 and NME 84 are quite clear — the predominant use governs. The retrofit requirement (IUE 85) does require consideration. The draft NPRM retrofit requirement includes "all commercial T 2 engines of 12,000 pounds thrust or greater, and all commercial T 4 engines (JT 8D)." This requirement suggests two further questions: (1) Does IUE 85 include commercial transports operated by non-commercial users? and (2) Should EPA reconsider the decision to exclude commercial aircraft using the JT 3D engine from this provision?

The number of commercial transports of the affected size (B 727, B 737, DC 9, B 707/720) operated by corporate aviators is small, but could increase as these aircraft are phased out of commercial service. The engines involved, principally the JT 8 and JT 3, are clearly "commercial" by predominant use, but corporate operators do not fall within the EPA definition of commercial operators.

The FAA fleet projections include some 200 aircraft presently using JT 3D engines as of 1/1/85. Under present noise regulations, these aircraft could continue to operate with 3D engines, provided that they were modified with quiet nacelles. While the FAA projections are not a guarantee that this aircraft will continue to be used in commercial service after 1/1/85, EPA should consider whether or not the NPRM should exempt JT 3D-powered aircraft.

FINANCIAL RISKS

The industry position toward the standards, particularly NME 84, is predictable. The producers and users of commercial aircraft complain that they are being asked to incur significant costs that will do nothing to improve engine or aircraft performance. The engine producers also claim that the technological changes required are so extensive that the standards should be applied only to newly certified, not to newly manufactured engines.

LMI does not find either argument convincing. We believe that it is sound policy to internalize the cost of pollution abatement. Implementation of the proposed standards will do this. Further, exemption of engines certified before 1984 would really be no control at all. Most of the fleet well into the 1990's will use pre-1984 engines or derivatives.

LMI believes that the major question to be resolved is whether or not the benefits to be derived from the regulation are greater than the costs of compliance. Recent EPA studies of the contribution of commercial aviation to NOx pollution were inconclusive. For this and other reasons, the draft NPRM is being reconsidered. One alternative would be to delay final NOx standard action for 18 months while further air quality studies are completed. Engine producers would be advised to continue development of NOx reduction technology as if the proposed 1984 date and standards were in force.

The NOx standards in the draft NPRM subject engine producers to substantial financial risks. The new proposal tends to increase these risks. In essence, the producers are being asked to make a major investment in development with no assurance that a commercial engine meeting proposed standards can be achieved. Both U.S. producers have unresolved major problems with staged combustors. Clearly these can be solved, but just as clearly compromises with low emissions may be required. Rolls-Royce faces the same problems and is further handicapped by being somewhat behind the U.S. producers in staged combustor technology.

Development and product improvement are normal processes for U.S. producers. Generally, commercial projects are funded through profits, but sufficient profits can only be generated if commercial prices include a provision for amortized development costs.[1] Although competition is restricted to two, or at the most three, engine producers, engine price is an important consideration. The regulation requires the producers to make a significant investment now and over the next few years that may be recovered only on sales after 1984.

Of course, if commercial prices include a provision for product improvement, funds for development will be generated in the period before 1984. These could be used for NME 84 development only at the expense of normal product improvement or derivative development. Thus, at the very least, there is a significant opportunity cost associated with NME 84, which applies not only to funding, but also to other resources such as engineering personnel and development equipment and facilities.

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[1] Historically, contracts for the procurement of production military aircraft engines have included a provision for further engine development work classified as product improvement. Development of new military engines through qualification is, of course, funded directly by Defense agencies.

Postponing the promulgation of final NOx standards for 18 months increases the risk to producers. LMI estimates that development costs for NME 84 could total more than $15 million per engine type over this period.[2]

SCHEDULE RISKS

The major disagreement between engine producers and EPA concerns the status of low emission technology. The implementation dates proposed by EPA were based (at least implicitly) on the assumption that the NASA low emission development programs had demonstrated the necessary technology. The engine producers concede this point, but claim that the deadlines do not allow enough time for engine development and adequate service testing.

In an economic study of this kind, such differences in technological assessment cannot be resolved. Yet it is worth pointing out that significant increases in compliance costs may be at stake.

- NME 81/IUE 85 - The potential cost increase resulting from insufficient service testing of HC/CO technology is $280 million, of which $170 million would accrue to U.S. airlines. It appears that the four-year period for retrofitting in-use engines is adequate and would not require the premature removal of a significant number of engines. Problems associated with NME 81 would, of course, affect retrofit engines. A one-year delay to 1982 and 1986 respectively would eliminate these potential costs. Note that one producer, General Electric, believed that a one-year service test program for the CF 6 might be sufficient.
- NME 84 - The potential cost increase associated with insufficient service testing for NME 84 engines is $425 million, of which $230 million would accrue to U.S. airlines. Note that General Electric proposes a two and one-half year service test program, starting in mid-1982 with production engines available 1/1/85. Pratt and Whitney estimates that service testing could begin in 1985 and that production engines could be made available only if service tests were eliminated. Rolls-Royce estimates that a two and one-half year service test program could be completed by the end of 1985 with production engines available by the spring of 1986. The magnitude of the potential cost penalty suggests careful review of the 1/1/84 implementation date.

JT 8D and NME 84

The original draft NPRM exempted newly manufactured engines below 20,000 pounds thrust from compliance with NME 84 NOx standards. The subsequent announcement of the DC 9–80 aircraft using the refanned JT 8D–209 (rated at 19,200 pounds thrust) gives new impetus to JT 8D sales and indicates that the engine could be in quantity production after 1984. EPA is therefore considering dropping the 20,000 pound threshold so that all existing and growth versions of the JT 8D are required to meet NOx standards.

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[2] This is a gross estimate prepared from data submitted by Pratt and Whitney and included as Appendix B. LMI time-phased the P&W estimate of cost to complete NME 84 development to obtain the $15 million total for 18 months.

The inclusion of this engine under the NOx standards became a consideration late in LMI's study. No estimates of the cost of compliance are available. In addition, the JT 8D is the only can-annular engine thus far considered for NME 84[3] — the JT 8D has nine combustion cannisters arranged in annular fashion. It is therefore difficult to scale estimates for other engines to obtain even a gross estimate of JT 8D cost of compliance.

The JT 8D engine was included in the NASA Pollution Reduction Technology Program and some configurations of a Vorbix-type staged combustor can were tested. The results showed a significant reduction in NOx emission compared to JT 8D–17 production engines, but CO was above standard. LMI has reviewed the final report prepared by Pratt and Whitney[4] to assess the technical problems remaining to be solved. The report deals primarily with emissions, but does show that:

- In terms of fuel nozzles, the JT 8D will be less complicated than annular engines. The number of fuel nozzles required will double.
- A considerable amount of fuel handling plumbing will be required that will have to be located in the hostile environment of the combustor. This could result in heated fuel being returned to the aircraft fuel supply.
- The combustors tested showed the same problems encountered with annular engines: carbon buildup, the need for a new and complex fuel management system, autoignition problems, and substantial changes in exit temperature patterns.
- A burner capable of simultaneous HC, CO, and NOx control would be more complex than any tested.

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[3] Note that the elimination of the 20,000 pound threshold would require other engines, particularly the Spey, to meet NME 84.

[4] R. Roberts, A.J. Fiorentino, and W. Greene, Pollution Technology Program, Can-Annular Engines, NASA CR-135027, May 1976.

- Rig tests only were conducted. No prototype engine tests with nine Vorbix combustors were included in the program.

Thus, the degree of development required for a low NOx JT 8D is at least equal to that required for annular engines. The necessity of including nine staged burner cans in each engine will probably add to both development costs and production time.

REFERENCES

The following documents, which include submissions to EPA, journal articles, speeches, briefing materials, and special studies prepared for LMI, were reviewed in the course of our study. Except where noted otherwise, the material is already in the public record.

Environmental Protection Agency

Aircraft Technology Assessment, Status of Gas Turbine Program, December 1976.

Control of Air Pollution from Aircraft and Aircraft Engines-Proposed Amendments to Standards, draft NPRM, August 1977.

Cost-Effectiveness Analysis of the Proposed Revisions in the Exhaust Emission Standards for New and In-Use Gas Turbine Aircraft Engines Based on Industry Submittals, AC77-02 (Draft), November 1977.

Pratt and Whitney

Status of Reduced Emission Combustors, Ref. No. 76-9304.

Control of Air Pollution from Aircraft and Aircraft Engines, Statement for EPA Public Hearings, January 27, 1976.

Information Supplement to Public Hearings, February 26, 1976.

Pollution Technology Programs, Can-Annular Engines, NASA CR 135027, May 1976.

Comments on the U.S. Environmental Protection Agency Aircraft Technology Assessment: Status of the Gas Turbine Program Report, April 11, 1977.

Presentation to EPA Mobil Source Air Pollution Control, Division of Emission Control Technology, May 11, 1977

Documentation of JT 9D Combustor Engineering Changes, July 7, 1977.

U.S. and International Commercial Jet Transport Fleets as of July 1, 1977, August 15, 1977.

General Electric

Product Information, AEG-2121.1,April 1977.

Emission Control Technology, presentation to LMI by D.W. Bahr, October 1977.

Plans/Approaches for Meeting CO/HC Standards, presentation to LMI by D.H. Bahr, October 1977.

Plans/Approaches for Meeting CO/HC/NOx Standards, presentation to LMI by D.H. Bahr, October 1977.

Introduction of Design Modifications Into Production Engines, study prepared for LMI by Dubell and Venable, November 1977.

Rolls-Royce

Status of Low Emission Technology, presentation to LMI, November 14, 1977.

Development Time Required to Meet Proposed Standards, presentation to LMI, November 14, 1977.

Combustion System Development, presentation to LMI, December 1977.

Civil Aeronautics Board

Air Carrier Financial Statistics, December 1976.

Air Carrier Major Investment, December 31, 1976.

Air Carrier Fuel Consumption 12-Month Period, December 31, 1976.

Certificated Route and Supplemental Air Carrier Fleet Inventory, March 31, 1977.

Certificated Route and Supplemental Air Carrier Aircraft on Order at March 31, 1977.

Air Carrier Traffic Statistics, June 1977.

Aircraft Operating Cost and Performance Report, Volume XI, July 1977.

Other

Aerospace Industries Association, Aerospace Facts and Figures, 1977/1978.

_______________, The Importance of Derivative Aircraft Programs (Draft), October 1977.

Airline Transport Association, Response to NPRM Entitled Extension of Compliance Dates for Emission Standards Applicable to the JT 3D Engine, January 12, 1976.

Air Transport Associations, Air Transport 1977.

Aviation Standard, World Aviation Directory, Fall 1977.

Bradley, Frederick M., Remarks to the Forum on the Future of Air Transportation, 13th Annual Meeting, American Institute of Aeronautics and Astronautics, July 11, 1977.

Daly, G.R., Cleaner Skies from the Jets, reprint from undesignated source.

Federal Aviation Agency, Aviation Forecasts, Fiscal Years 1977-1988, September 1976.

______________, Equipment Forecast for (Major) Air Carrier Airports, 1975-2000, November 1977.

Grayson, K., Spectrometric Oil Analysis Program (SOAP)-An Essential Ingredient of Engine Health Monitoring, American Airlines, March 1, 1974.

______________, Improved Maintenance Practices-The Airlines' Contribution to Lower Ownership Costs, American Airlines 760504, May 1976.

Nelson, A.W., Development of a Reduced Smoke Combustor for the JT 3D Engine, SAE 740484, May 1974.

APPENDIX A. COSTS OF COMPLIANCE

INTRODUCTION

The draft NPRM circulated in late summer 1977 contained new gaseous emission standards for commercial aircraft engines. This appendix develops estimated costs for users of these engines (airlines) to comply with the NPRM's three major requirements:

(1) NME 81 - All newly manufactured engines with 6,000 pounds or more of thrust after 1/1/81 will meet revised hydrocarbon (HC) and carbon monoxide (CO) standards.

(2) NME 84 - All newly manufactured engines with 20,000 pounds or more of thrust will meet revised standards for oxides of nitrogen (NOx).

(3) IUE 85 - All in-use engines with 12,000 pounds or more of thrust will be modified to meet the 1981 HC/CO standards by 1/1/85.

The requirement that all engines certified after 1/1/84 meet the NOx requirement is not addressed here. Engine producers are presently concentrating on derivatives of existing core engines, particularly "clipped fans," and newly certified versions of these derivatives can be assumed to be included in the NME category.

The cost of compliance was estimated in two phases: (1) determination of the unit cost impact on particular engines, and (2) development of time-phased total fleet cost for the period 1981-1988. The unit cost per engine type includes the price increments associated with NME 81 and NME 84, the cost of modifying an engine to meet IUE 85, and the per-engine change in engine maintenance or operating costs. The time-phased total fleet costs were based on the application of these unit costs to the projected aircraft fleet.

The process of estimating the cost of compliance is relatively straightforward. The uncertainty associated with the estimates reflects the ambiguous future of the airline industry. Although most forecasters predict substantial growth in the demand for air travel over the next decade, it is not clear just how the airlines will meet it. Obviously, expanded capacity will be required and aging aircraft must be replaced. Still, no common design goal for the next generation of aircraft has emerged, since the airlines have different needs in terms of their route structures and different potential for making the required investment. Thus, Boeing has delayed the development of final designs for the proposed 7X7 and 7N7 aircraft, but is offering derivatives of its current aircraft. Lockheed and McDonnell-Douglas are also concentrating on derivative development. The manufacturers are offering up- and down-scaled versions of the 747, L 1011, DC 10, and McDonnellDouglas recently announced a super stretched version of the DC 9 designated the DC 9 80.

The engine manufacturers are ready to meet the thrust requirements that the airframe producers will desire. Several new engines are in development and nearing the certification stage. These include the General Electric CFM 56 and CF 34, the Pratt and Whitney JT 10D, and the Rolls-Royce M 45 already certified for the VFW 614. All producers have or are developing clipped fan versions of the basic large engines for application on new wide-body aircraft designs.

U.S. FLEET PROJECTIONS

LMI used the projections of the demand for air transportation and the air carrier fleet that are prepared annually by FAA.[1] These estimates are internally consistent, that is, demand in terms of passengers, passenger miles and departures, is matched to the projected fleet. They also reflect the impact of noise regulations, an important consideration often omitted from other projections. Because FAA projections show inventory only and do not indicate additions to, or retirements from, the fleet, LMI has supplemented their estimates with information prepared by the Air Transportation Association (ATA) and by the EPA.[2]

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[1] Aviation Forecasts, Fiscal Years 1978-1989, FAA-AVP, December 1977.

[2] R. S. Wilcox and R. Munt, Cost-Effectiveness Analysis of the Proposed Revisions in the Exhaust Emission Standards for New and In-Use Gas Turbine Engines Based on Industry Submittals, EPA Draft Report AC77-02, November 1977.

Table A-1 shows the FAA fleet estimates as of January 1 for the years 1977, 1980, 1985, and 1989. Table A-2 shows a comparison, as applicable, of the FAA, EPA and ATA estimates. Note that aircraft are classified by body size (wide and regular) and by the number of engines. Aircraft included in each category are shown in Table A-3.

TABLE A-1. FAA ESTIMATE OF THE U.S. AIR CARRIER FLEET AS OF JANUARY 1

Jet Aircraft Only

	1977	1980	1985	1989
Standard Body				
4 Engine Passenger	399	357	146	131
4 Engine Cargo	88	80	56	51
Total	487	437	202	182
3 Engine Passenger	823	923	913	840
2 Engine Passenger	536	631	625	840
Wide Body				
4 Engine Passenger	94	119	209	255
4 Engine Cargo	12	19	32	37
Total	106	138	241	292
3 Engine Passenger	202	230	450	645
3 Engine Cargo	0	2	13	16
Total	202	232	463	661
2 Engine Passenger	0	32	135	239
Total Fleet	2154	2393	2779	3054

FAA predicts that the airline inventory will increase by more than 40% by 1988 and include considerable shifts to large-capacity, wide body aircraft. The EPA projections, based on an earlier 1976 study by Munt, omit consideration of the four-engine regular-body aircraft on the assumption that they will be phased out by 1985. FAA's predictions reflect the opinions of some airlines that the more recent versions of both B 707's and DC 8's may remain in the inventory considerably longer than 1985. This implies some

TABLE A-2. COMPARISON OF FAA, EPA AND ATA PROJECTIONS

	1979			1984			1988		
	FAA	EPA	ATA	FAA	EPA	ATA	FAA	EPA	ATA
Wide Body									
4 Engine	138	164	112	241	271	138	292	424	NA
3 Engine	232	305	230	463	462	293	661	658	NA
2 Engine	32	0	0	135	0	0	239	0	NA
Regular Body									
4 Engine	437	NA	334	202	NA	231	182	NA	NA
3 Engine (a)	923	840	970	913	923	959	840	1091	NA
2 Engine	631	684	524	825	771	467	840	753	NA
Fleet	2393		2170	2779		2088	3054		

(a) EPA estimates for three engine regular body aircraft include "super stretched" aircraft as follows: 1979-0; 1984-244; 1988-528

NA = Not Available.

TABLE A-3. AIRCRAFT IN EACH CATEGORY

Wide Body
4 Engine - Boeing 747
3 Engine - DC 10, L 1011
2 Engine - A 300

Regular Body
4 Engine - B 707, B 720, DC 8, CV 990, COMET, VC 10
3 Engine - B 727, Trident
2 Engine - B 737, DC 9, BAC 111, Mercure, F 28, VFW 614, Caravelle

Note: No Soviet aircraft were considered in this.

quieting process such as the application of soundproofing or the reengining of the aircraft. The ATA projections, prepared in June 1977, were obtained from a survey of its members and are represented as a trend projection rather than an "inventory plan."

Some of the differences between the ATA and FAA estimates can be explained by differences in coverage. The FAA projections include all commercial operators; ATA's were limited to their membership. Table A-4 shows the aircraft owned by various groups

TABLE A-4. COMPARISON OF INVENTORY FROM VARIOUS SOURCES AS OF 12/31/76

	WORLD AVIATION DIRECTORY								
	Trunks & Pan Am	Local	All Cargo	Supple-mentals	Alaska & Hawaii	Intra State	Total	ATA	FAA
B 747	101	0	4	3	0	0	108	103	106
DC 10	122	0	0	3	0	0	125	122	NA
L 1011	82	0	0	0	0	2	84	79	NA
3 ENG WB	204	0	0	3	0	2	209	201	202
B 707/720	284	0	0	5	0	0	289	278	NA
DC 8	148	0	35	35	0	0	218	158	NA
4 ENG	432	0	35	40	0	0	507	436	487
B 727-100	376	0	0	5	10	3	394	386	NA
B 727-200	413	3	0	0	0	23	439	416	NA
3 ENG	789	3	0	5	10	26	833	802	823
B 737	83	41	0	0	11	18	153	138	NA
DC 9	158	186	0	0	9	6	359	355	NA
BAC 111	1	31	0	0	0	0	32	31	NA
2 ENG	242	258	0	0	20	24	544	524	536
Total	1768	261	39	51	30	52	2201	2066	2154

Sources: World Aviation Directory, Fall 1977
ATA estimate dated 6/29/76. Includes ATA members only
FAA supplement to forecasts published December 1977

of commercial operators, along with the FAA and ATA inventories as of 12/31/76. Note that the data for commercial operators, taken from the World Aviation Directory, include two B 747 aircraft on lease outside of the U.S. and a total of 21 inactive aircraft (14 for trunks and 7 for supplemental carriers). The ATA data include both the supplementals and the intra-state carriers. Note that the EPA projections begin in 1979 and therefore could not be included in this comparison.

The 2200 aircraft included in the World Aviation Directory count do not represent all the commercial jet aircraft operating in the U.S. The National Business Aviation Association membership fleet, that is, corporate operators classified as general aviation, includes 3 B 707/720, 1 B 737, 1 DC 9, 1 F 28, and 19 BAC 111 aircraft. It is quite possible that additional commercial jets will be added to the business fleet as they are phased out by airline operators. Such aircraft have not been considered in this study, however, because of the relatively small numbers involved and their uncertainty.

Additions and Retirements

The FAA projections provide the basis for estimating the number of engines which fall in each of the regulatory categories. These numbers cannot be determined directly from the FAA inventory data, however, because older, less efficient aircraft will be retired and newer aircraft will be added to the fleet.

The EPA and ATA estimates both include additions and retirements, but the EPA assumptions about the 7X7/7N7 aircraft are open to question. That aircraft cannot enter the inventory as early as 1981, nor in the numbers projected by EPA. LMI has therefore assumed that the aircraft is included in an appropriate category of the FAA projections (2EWB, 3EWB, 2ERB). Neither EPA nor ATA considered two-engine wide body aircraft (2EWB) which are included in sizeable numbers in the FAA inventories. LMI believes that the category is properly included, particularly since Eastern Airlines is operating 4 A 300 airbus aircraft on a trial basis.

The ATA and EPA projections are quite different in some respects. ATA shows that the airlines expect to buy 314 B 727-200, 7 B 737-200, 16 DC 9-30, and 75 DC 9–50 aircraft durign the 1977-85 period. All of these aircraft meet the present noise regulations and can be productively used on present route structures. ATA also expects the airlines will retire 162 B 727, 70 B 737, 85 DC 9, and 34 B 747 aircraft which do not meet the present regulations.

The EPA projections include moderate procurement (15-20 aircraft) of 2ERB's through 1986, with 76 aircraft per year thereafter, and no procurements of 3ERB aircraft. EPA expects moderate retirements of 2ERB through 1983 with accelerated retirements thereafter. It is expected that the number of 3ERB aircraft will be reduced from 840 in 1980 to 563 in 1988, a total of 277 retirements.

LMI used the FAA inventory counts for the years 1980, 1983, 1984, and 1988 as control totals and the ATA retirement rates through 1985 to calculate additions to the fleet. The additions, by aircraft type, are shown in Table A-5, along with the additions projected by ATA and EPA. The major differences between EPA and LMI are the 2EWB aircraft (not in the table) where LMI (and FAA) project a fleet of 239 aircraft, and the addition of almost 150 3ERB aircraft through 1985. Note also that the FAA projects considerable fewer B 747 (4EWB) aircraft than EPA.

Table A-6 shows a buildup of candidate aircraft that fall into each of the regulatory classes. The top part of the table shows the inventories for each of the key years along with the additions and retirements in the key periods. The bottom half of the table summarizes the number of aircraft in each of the regulatory categories (NME 81, NME 84, and IUE 85).

Table A-7 uses these aircraft to estimate the number of engines required for each category of aircraft. The engine total includes both slip sets (engines installed on aircraft) and spare engines. A factor of 25% was used for the modern, complex engines

TABLE A-5. COMPARISON OF ESTIMATED NEW AIRCRAFT ADDED TO FLEET

U. S. AIRLINES

	4 Engine Wide Body			3 Engine Wide Body			3 Engine Regular Body			2 Engine Regular Body		
	ATA	EPA	LMI	ATA	EPA	LMI	ATA	EPA(1)	LMI	ATA	EPA	LMI
1979	3	17	26	15	22	11	40	0	45	18	37	64
1980	9	20	20	14	31	40	53	0	20	19	32	60
1981	4	20	20	16	31	42	21	77	20	11	19	60
1982	4	21	20	16	33	48	21	83	20	11	14	50
1983	4	29	26	9	40	55	4	84	18	4	5	40
1984	4	32	30	9	42	46	3	83	16	3	14	25
1985	5	36	13	9	47	46	3	78	10	3	16	21
1986	NA	40	13	NA	51	50	NA	68	.6	NA	16	21
1987	NA	45	13	NA	56	50	NA	55	5	NA	76	21
1988	NA	70	12	NA	61	52	NA	89	4	NA	76	21
Total	33	301	193	88	414	440	145	617	164	69	305	383

[1] EPA figures represent "super stretched" 3 engine regular body aircraft.

TABLE A-6. BUILDUP OF CANDIDATE AIRCRAFT

	Inventory 1980	1981-83		Inventory 1983	1984		Inventory 1984	1985-88		Inventory 1988
		RET	ADD		RET	ADD		RET	ADD	
Wide Body										
4 Engine	145	0	66	211	0	30	241	0	51	292
3 Engine	272	0	145	417	0	46	463	0	198	661
2 Engine	52	0	62	114	0	21	135	0	104	239
Regular Body										
4 Engine	387	185	0	202	0	0	202	20	0	182
3 Engine	922	62	58	918	21	16	913	98	25	840
2 Engine	683	23	150	810	10	25	825	69	84	840
Fleet	2461	270	481	2672	31	138	2779	187	462	3054

NME 81	NME 84	IUE 85	Total	
Wide Body				
4 Engine	66	81	145	292
3 Engine	145	244	272	661
2 Engine	62	125	52	239
Regular Body				
4 Engine	0	0	202	202
3 Engine	58	41	839	938
2 Engine	150	109	650	909
Total	481	600	2160	3241

TABLE A-7. ENGINES REQUIRED FOR PROJECTED U.S. FLEET

	No. of Aircraft	Engines		
		Ship Sets	Spares	Total
NME 81				
4 Engine Wide Body	66	264	66	330
3 Engine Wide Body	145	435	105	540
2 Engine Wide Body	62	124	31	155
3 Engine Regular Body	58	174	36	210
2 Engine Regular Body	150	300	60	360
NME 84				
4 Engine Wide Body	81	324	81	405
3 Engine Wide Body	244	732	183	915
2 Engine Wide Body	125	250	60	310
3 Engine Regular Body	41	123	22	145
2 Engine Regular Body	109	218	42	260
In Use Modification 85				
4 Engine Wide Body	145	580	145	725
3 Engine Wide Body	272	816	204	1020
2 Engine Wide Body	52	104	26	130
3 Engine Regular Body	839	2517	503	3020
2 Engine Regular Body	650	1300	260	1560

used on the wide bodies (JT 9, CF 6, and RB 211) and 20% for the more mature engines used on the regular bodies (presently the JT 8). Note that, at this point, no estimates of engines required to operate the 200 4ERB (B 707/DC 8) aircraft are included in the inventory. These aircraft represent a special case and are excluded from consideration in this appendix.

FOREIGN FLEET PROJECTIONS

U.S.-produced aircraft make up more than 75% of the total aircraft operated by foreign airlines. Most of the other aircraft are powered by engines produced by Pratt and Whitney, General Electric, or Rolls-Royce. The French engine producer SNECMA has joint venture programs with Rolls-Royce on the M 45 engine and with GE on the CFM 56. Table A-8 shows the U.S. and foreign fleets by aircraft type, excluding the 112 aircraft produced by the USSR. The foreign fleet calculated as a percentage of the U.S. fleet for key aircraft categories was used to project the number of engines required by foreign operators.

TABLE A-8. COMPARISON OF U.S. AND FOREIGN FLEETS AEROSPACE FACTS & FIGURES ESTIMATES 1976

	1976 Inventory			Foreign As a Percent of U.S.
	World	U.S.	Foreign	
Wide Body				
4 Engine				
B 747	268	105	163	155.2%
3 Engine				
DC 10	218	125	93	74.4%
L 1011	126	77	49	63.6
Total	344	202	142	70.3%
2 Engine				
A 300	24	0	24	-
Regular Body				
4 Engine				
B 707/720	719	265	454	171.3%
VC 10	26	0	26	-
CV 880/990	18	0	18	-
DC 8	482	211	271	128.4
HS Comet	17	0	17	-
Total	1262	476	786	165.1%
3 Engine				
B 727	1185	820	365	44.5%
HS Trident	86	0	86	-
Total	1271	820	451	55.0%
2 Engine				
B 737	436	152	284	186.8%
DC 9	758	352	406	115.3
BAC 111	163	31	132	425.8
Mercure	10	0	10	-
F 28	81	0	81	-
VFW 614	6	0	6	-
Caravelle	187	0	187	-
Total	1641	535	1106	206.7%
Fleet	4810	2138	2672	125.0%

Only a few of the regular body aircraft owned by foreign carriers operate to and from the U.S. LMI examined the Official Airline Guide for December 1977 to isolate the foreign operators (essentially North American or Caribbean) who use these classes of aircraft in the U.S. The airlines and their aircraft fleets are shown in Table A-9. Note that Air Canada offers frequent service from Canadian points to Florida, utilizing B 747's and L 1011's, while CP Air supplies B 747 Pacific flights through Hawaii.

TABLE A-9. AIRCRAFT INVENTORY - NORTH AND CENTRAL AMERICAN AIRLINES WITH FLIGHTS TO U.S.
December 31, 1976

	Wide Body			Regular Body		
	4 Eng	3 Eng	2 Eng	4 Eng	3 Eng	2 Eng
Air Canada	6	10	0	31	14	51
CP Air	4	0	0	12	2	7
Pacific Western	0	0	0	2	2	13
Mexicana	0	0	0	0	23	0
Aeromexico	0	2	0	5	0	16
Bahamas Air	0	0	0	0	0	3
Caynian Airways	0	0	0	0	0	1
Air Jamaica	0	0	0	6	4	3
BWIA	0	0	0	8	0	3
ALM	0	0	0	0	0	3
Total	10	12	0	64	45	100

Table A-10 shows the total engines required to satisfy U.S. and foreign requirements broken down by regulatory category. For IUE 85 requirements, LMI assumed that only 80% of the foreign B 747 fleet and only 50% of the 3EWB fleet would be modified, to reflect the fact that some operators and some routes do not include U.S. stops. The 3ERB and 2ERB projections for IUE 85 include aircraft for those airlines shown on Table A-9.

UNIT COST OF COMPLIANCE

The engines considered in this study include the JT 9D, JT 10D, JT 8D, CF 6, CFM 56, RB211, M 45, and the Spey. The JT 10D, CFM 56, and M 45 are either not certified or not used on aircraft likely to be used in the U.S. The Spey-powered F 28 twin

TABLE A-10. ESTIMATED TOTAL ENGINES REQUIRED 1981-1988

Type Aircraft	U.S. Engines	Factor	Engines	
			Foreign	Total
NME 81				
Wide Body				
4 Engine	330	1.5	495	825
3 Engine	540	.7	380	920
2 Engine	155	1.0	155	310
Regular Body				
3 Engine	210	.15	30	240
2 Engine	360	1.0	360	720
NME 84				
Wide Body				
4 Engine	405	1.5	605	1010
3 Engine	915	.7	640	1555
2 Engine	310	1.0	310	620
Regular Body				
3 Engine	145	.15	20	165
2 Engine	260	1.0	260	520
IUE 85				
Wide Body				
4 Engine	725	(1.5)(.8)	875	1600
3 Engine	1020	(.7)(.5)	350	1370
2 Engine	130	0	0	130
Regular Body				
3 Engine	3020	NA	180	3200
2 Engine	1560	NA	240	1800

jet is being considered by at least one U.S. carrier and can be assumed to be included in the 2ERB cateogry. The CFM 56, in the 22,000 pounds thrust range, could be used to reengine DC 8 to B 707 aircraft[3] (not considered in this appendix) or in a derivative version for newly produced 2ERB aircraft. (No such program has been announced.) The JT 10D, in the 25-35,000 pounds thrust range, is a candidate for the new Boeing 7X7/7N7 design when finalized, but has no other announced application. The M 45, rated at 7,600 pounds thrust, does not seem to be a factor for the class of aircraft considered here.[4] Because of these factors, LMI concentrated its efforts on estimating the cost impacts of the regulation on the JT 9D, JT 8D and CF 6 engines.

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[3] Boeing and GE have a joint program to certify a CFM 56 version of the B 707.

LMI received assistance from the three engine producers and several airlines (national trunk, regional trunk, and international carriers were represented) in developing the unit costs presented here. All companies visited were helpful in identifying potential problems and supplied the best available data. GE did not feel that a revised cost estimate would increase accuracy and instead broke its estimates of development costs down into more meaningful categories. Rolls-Royce and Pratt and Whitney did revise their cost estimates and each went through a complete, although naturally preliminary pricing analysis. Pratt and Whitney went one step further, and prepared a complete cost package including their estimates of impacts on engine maintenance cost due to premature engine removal and impacts on immature combustors in the field. This package is included as Appendix B.

The unit cost factors required for each engine are as follows:

- Price increment for NME 81 and NME 84, including prorated development costs
- Modification of parts and labor costs associated with IUE 85
- Impact on engine maintenance cost resulting from NME 81/IUE 85 and NME 84
- Fuel consumption impacts
- Costs associated with schedule problems, that is, premature engine removal and inadequate service tests.

Price Increments and Modification Costs

The engine manufacturers have submitted cost estimates covering development of low emission engines and the expected increase in price. The estimates vary as to depth and coverage, are not precisely comparable, and are difficult to substantiate. LMI knows of no parametric engine-cost-estimating models applicable to this problem. Several such models exist, but they are designed to produce estimates of new core engines and rely on such cost-determining variables as thrust, engine weight, quantity required, and in some cases, speed of the aircraft. The U.S. Navy has a model that can be used to predict the cost of derivative engines, but the performance variables considered are not useful for our problem. Reasoned judgment was therefore our only recourse in assessing the validity of the various estimates.

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[4] The VFW-Fokker 614 program was recently terminated.

New core engines are very costly to develop. Pratt and Whitney has, for example, joined a consortium of foreign producers to develop the JT 10D. The partners are contributing $500 million on a shared basis to develop the engine through certification. Engine development continues well after certification and industry sources estimate that the cost after certification is at least equal to that before. Airline sources tended to confirm this, and one claimed that if airline costs were included, the factor would be two or three times precertification costs. Thus, a rule-of-thumb estimate for new engine development is $1 billion.

The low emission engines discussed here are not, of course, new engines. Moreover, the basic combustor designs have been demonstrated through the NASA research. Nevertheless, considerable development work remains to be completed before a commercially acceptable engine can be produced. The question to be resolved is the length of time required for development and how much it will cost.

The combustor is the heart of a modern fan engine. Unlike compressors, fans or turbines; their design is only partially susceptible to analytic processes, and, in many cases, final designs are accomplished through trial-and-error. This means that although many of the other engine components can be scaled up or down in size, a combustor designed for one set of requirements will not necessarily be suitable in a different application. Moreover, even relatively simple changes in combustors require a significant amount of testing before they are commercially acceptable. This fact is amply illustrated by the JT 9 and JT 3 smoke programs and the CF 6 "ruggedized combustor" program.

The airlines estimate that "hot sector" (combustor and turbine) maintenance makes up 60-80% of total engine maintenance for large fan engines. The outputs of the combustor are closely matched to the design input requirements of the turbine. Both operate in very hostile environments (temperature and pressure). Any mismatch will seriously reduce turbine component life.

Combustor durability is another important factor. Airlines desire at least 4000 engine hours between combustor repairs. The older engines meet and often exceed this figure. Many JT 3 engines have more than 20,000 hours without repair and a recent Pratt and Whitney release reported more than 10,000 hours on an Air Canada JT 9D. The RB 211 and CF 6, being less mature, have not achieved these long intervals between overhauls.

Based on these considerations, LMI believes that significant development work remains to be accomplished. The NME 81 standard can be met, although it is doubtful that the 1/1/81 date will allow enough time for service evaluation. Both GE and Rolls-Royce propose to use sector burning as a means of controlling HC/CO emissions. P&W proposes only changes in fuel nozzles and burner geometry.

All producers plan staged combustors to meet NME 84 standards. These burners are a radical departure from conventional technology and will be much more complex than the existing ones. While the basic concepts have been demonstrated, major problems remain to be solved. Very complex fuel control systems will be required, along with methods for purging fuel from main stage nozzles when not in use. These requirements are in addition to the usual ones of assuring that combustor output temperature patterns are compatible with the turbine, that the combustor has adequate service life, and that the final design is sufficiently simplified to be commercially acceptable.

The GE and P&W estimates of development costs for the NME 81 standards are roughly equivalent: $16 million (1976 dollars) for GE (CF) and $19.5 (1978 dollars) for

P&W (JT 9). LMI regards the GE task as more demanding since sector burning is involved. In general, however, we believe that P&W has taken a conservative approach whereas GE has taken an overly optimistic one.

For NME 84, GE estimates development costs as $80 million (1976 dollars) and P&W as $116 million (1978 dollars). GE appears to have estimated a 100% success program and P&W appears to be conservative.

P&W and Rolls-Royce went through a pricing exercise to determine a price increment for the engines involved. The increment included amortization of development costs over their anticipated sales for the selected recovery period and a return on investment satisfactory to the company. The factors used were regarded as proprietary information by the companies. The price increments were as follows (thousands of dollars):

	NME 81	NME 84	IUE 85
JT 9D (1978)	$ 50	$309	$150
JT 10D (1978)	NA	299	NA
JT 8D (1978)	12	NA	35
RB 211 (1977)	66	150	110
Spey (1977)	96	NA	NA

GE did not do a pricing exercise, but instead provided estimated development costs (shown above) and expected increases in the price of production engines, excluding consideration of development costs. These were: NME 81 - $10,000, NME 84 - $100,000, and IUE 85 – $90,000. No cost estimates for the CFM 56 were submitted. The CF 6 factors were converted to engine price increments comparable to those above by assuming a 12% rate of return and amortizing development over expected worldwide engine sales. If NME 81 development costs are amortized over all retrofit as well as new engines, the price increments would be: NME 81 - $26,000, IUE 85 - $105,000. The NME 84 factor would be $199,000.

LMI believes that there is so much uncertainty in the projection of engine requirements by type of aircraft (Table A-10) that any attempt to project specific makes of engines is unwarranted. Instead, average price increments by aircraft type based on the costs discussed were developed. These are shown in Table A-11. Note that the table assumes that all two- and three-engine regular body aircraft will be powered by a JT 8D derivative. This assumption yields a minimum cost of compliance. It is possible that some or all 2ERB aircraft produced after 1982 or 1983 could use the CFM 56. For analysis purposes it has been assumed that the price increment for the CFM 56 for NME 84 is $100,000.

TABLE A-11. UNIT COST OF COMPLIANCE ENGINE PRICE INCREMENTS
(Thousands of Dollars)

	NME 81		NME 84		IUE 85
	Price Increment	% Increase	Price Increment	% Increase	Mod Kit
RB 211	$66	4.3%	$150	9.7%	$110
Spey	96	16.4	NA	NA	NA
JT 9	50		309		150
JT 8	12		NA	NA	35
CF 6	26		199		105
Use For Analysis					
Wide Body					
4 Engine	$50		$300		$150
3 Engine	40		200		110
2 Engine	40		200		110
Regular Body					
4 Engine	NA		NA		NA
3 Engine	12		NA		35
2 Engine	12		NA		35

NA = Not Applicable

Maintenance Costs

Increases in complexity almost without exception lead to increases in maintenance costs. This is particularly true for combustors since the burner can greatly influence turbine life. All airlines contacted believed that the staged combustor engines for NME 84 will present serious maintenance problems and result in greater maintenance costs. None could quantify the impact without considerably more detail than was available at this time. The P&W submission (Appendix B) did attempt to estimate maintenance cost increases under a variety of assumptions. These were used to prepare Table A-12, which develops incremental maintenance costs per engine by aircraft type. The table includes 1976 operational data used to calculate average operating hours per engine so that cost per engine in the fleet could be computed. The range of costs presented for NME 84 represent cost increments under two assumptions: (1) that NME 84 burner life is equal to that achieved today, and (2) that burner life is reduced by 50%.

Fuel Consumption

All of the engine producers claimed that there would be no change in specific fuel consumption associated with the engine modifications required to obtain low emissions. Two factors may affect fuel consumption, however. First, HC/CO reductions are achieved by increasing the combustor efficiency at idle by as much as 5% - the improved combustors will burn a leaner mixture of fuel and air. This will result in less fuel burned per flight even though fuel flow conditions other than at idle will not change. Second, the NME 84 engines will weigh more than existing ones because of their complexity and the plumbing required to dispense fuel to the staged burners. This extra weight will cause an aircraft to burn more fuel to carry a given payload on a given flight.

EPA estimated that a typical flight includes 26 minutes on the ground when the engine is in either an idle or taxi mode. LMI used this estimate along with historical data to calculate the average idle/taxi mode time by aircraft type. Idle fuel flows could then

TABLE A-12. INCREMENTAL MAINTENANCE COST BY AIRCRAFT TYPE

					Maintenance/Engine Hour			Incremental Cost/Engine	
			Average Hours			Increment			
	Block Hours	Aircraft	Aircraft	Engine	1976	NME 81	NME 84	NME 81	NME 84
B 747	332,901	101	3296	2650	$110	$ 4	$11-46	$10.6	$29.2-121.9
DC 10	399,824	122	3277	2620	93				
L 1011	239,309	82	2918	2340	103				
	639,133	204	3133	2500	98	$3.5	$10-40	$ 8.8	$25.0-100.0
B 727	2,331,290	789	2955	2460	33	0.2	NA	0.5	NA
B 737	190,368	73	2608	2175	58				
DC 9	520,866	158	3297	2750	33				
	711,234	231	3079	2570	44	$ 0.3	NA	$ 0.7	NA

NOTE: Block hours, aircraft, average hours and 1976 maintenance cost per engine hour were calculated from CAB Form 41 data. Cost increments were calculated from P&W submission.

be applied along with estimated savings to obtain savings per aircraft type per year. These savings are shown in Table A-13.

LMI used industry data to estimate the fuel penalty incurred from the increased NME 84 engine weight. The factors are shown in Table A-14.

TABLE A-13. FUEL SAVINGS PER YEAR

	Aircraft Type				
	4EWB	3EWB	2EWB	3ERB	2ERB
Ground Time (Min)					
Taxi	22.0	19.1	12.0	13.4	9.9
Idle	14.0	14.0	14.0	14.0	14.0
Total	36.0	33.1	26.0	27.4	23.9
Hours	0.60	0.55	0.43	.48	.40
Fuel Flow (gal/hr)	270	200	180	170	170
Fuel per Flight (gal)	162	110	78	78	68
Savings Factor	.05	.05	.05	.01	.01
Savings per Flight (gal)	8.1	5.5	3.9	0.8	0.7
Flights per Engine	3200	3260	5000	5380	6290
Savings/Yr (gallons)	25920	17984	19500	4177	4259

TABLE A-14. FUEL PENALTY PER ENGINE YEAR

	Aircraft Type		
	4EWB	3EWB	2EWB
Engine Weight Increase	300	200	200
Cost per Pound per Year	$ 8	$ 5	$ 4
Cost per Engine per Year	$2400	$1000	$800

Other Fuel Factors

Three other types of cost should be considered: costs associated with reduced service life for the NME 84 combustors, costs associated with the premature introduction of engines into service, and costs associated with the premature removal of engines to meet the IUE 85 schedule.

All engine producers believe it will be difficult, if not impossible, to produce a staged burner that is as reliable as present combustors. P&W supplied estimates of the increased maintenance costs if the burners achieve only half of normal life. This should be used only for a "worst case" estimate.

All producers are concerned that the proposed implementation dates will not allow adequate service testing of engines. The history of both the JT 8D and JT 3D smoke reduction programs show what can happen during service tests and both programs were much simpler in scope than those required for this analysis. P&W supplied average shop visit costs for its engines, and suggests that the NME 81 and IUE 85 schedules are such that each engine introduced prematurely will have one additional shop visit before problems are solved. For NME 84, P&W suggests that engines introduced in 1984 will require two extra shop visits while engines introduced in 1985 and 1986 will require one extra visit before all problems can be isolated and solved. These penalties, like the service life discussed above, are useful only to determine a worst case.

It is possible that the manual overhaul cycle will not allow all in-use engines to be modified by 1/1/85. If this occurs, engines would be removed from the aircraft prematurely, and the airlines would incur extra costs. These costs would include the cost of removing and replacing the engine, tearing it down to remove and replace or modify the combustor, and building up of a usable engine.

The per-engine costs associated with these penalties are shown in Table A-15. The burner life penalty for NME 84 engines was obtained from the data in Table A-12. The average cost per shop visit is shown as a tool for calculating the service test penalty, and the cost of an engine removal plus teardown and buildup is shown for the premature engine removal penalty. The time between overhauls for enginns was estimated by LMI from data supplied by the airlines.

TABLE A-15. FACTORS FOR POTENTIAL PENALTIES

Half Burner Life (NME 84)

4EWB	$ 92,700	per engine per year
3EWB	75,000	
2EWB	75,000	

Service Test Penalty

NME 81/IUE 85

4EWB	$180,000	per engine shop visit
3EWB	160,000	
2EWB	160,000	
3ERB	85,000	
2ERB	85,000	

NME 84

4EWB	$210,000	per engine shop visit
3EWB	185,000	
2EWB	185,000	

Premature Engine Removals (IUE 85)

	Time Between Overhauls		Cost Per Engine		
	Engine	Combustor	Removal	Increment	Total
4EWB	3000	4500	$1800	$36,000	$37,800
3EWB	2500	4500	1800	24,000	25,800
2EWB	2500	4500	1800	24,000	25,800
3ERB	4500	5000	1000	16,000	17,000
2ERB	4500	5000	1000	16,000	17,000

COST OF COMPLIANCE

The cost factors required for calculating the cost of compliance are summarized in Table A-16, while the engines operated each year in each aircraft group are shown in Table A-17 by regulatory category. Information from these tables can be combined to estimate the cost of compliance under a variety of conditions.

Minimum Cost of Compliance

LMI defines the minimum cost of compliance as the costs of compliance assuming that all schedules are met with no penalties. Under those conditions, the costs will total

TABLE A-16. FACTORS FOR CALCULATING COST OF COMPLIANCE

(Thousands of Dollars per Engine)

	Wide Body			Regular Body	
	4ENG	3ENG	2ENG	3ENG	2ENG
NME 81/IUE 85					
Engine Price	$ 50.0	$ 40.0	$ 40.0	$ 12.0	$ 12.0
Retrofit Kits	150.0	110.0	110.0	35.0	35.0
Maintenance	10.6	8.8	8.8	0.5	0.7
Fuel Saving	25.9	18.0	19.5	4.2	4.3
Service Test ($/visit)	180.0	160.0	160.0	85.0	85.0
Premature Removal					
Remove Engine	1.8	1.8	1.8	1.0	1.0
Increment	36.0	24.0	24.0	16.0	16.0
TBO-Engine (hrs)	3000	2500	2500	4500	4500
-Burner (hrs)	4500	4500	4500	5000	5000
NME 84					
Engine Price	300.0	200.0	200.0	--	--
Maintenance	29.2	25.0	25.0	--	--
Fuel Saving	25.9	18.0	19.5	--	--
Fuel Penalty	2.4	1.0	0.8	--	--
Half Life	92.7	75.0	75.0	--	--
Service Test ($/visit)	210.0	185.0	185.0	--	--

TABLE A-17. ENGINES USED TO CALCULATE COST OF COMPLIANCE

	Wide Body			Regular Body	
	4ENG	3ENG	2ENG	3ENG	2ENG
NME 81					
New Engines -U.S.	330	540	155	355	620
-Foreign	495	380	155	50	360
Cumulative Years of Engine Operation -U.S.	2115	3470	1005	1845	3058
-Foreign	3170	2430	1000	160	1000
IUE 85					
Engines Modified -U.S.	725	1020	130	3020	1560
-Foreign	875	350	0	180	240
Cumulative Years of Engine Operation -U.S.	4238	5850	753	17490	9032
-Foreign	5086	2048	0	1040	1390
NME 84					
New Engines -U.S.	405	915	310	--	--
-Foreign	605	640	--	--	--
Cumulative Years of Engine Operation -U.S.	1194	2230	775	--	--
-Foreign	1790	1560	--	--	--

more than $1.5 billion, $990 million of which will be incurred by U.S. operators. NME 81 would cost $135 million, IUE 85 would cost $573 million, and NME 84 would cost $815 million. Details of these costs are shown in Table A-18.

Calculation of Cost Penalties

P&W estimated that the required IUE 85 modifications could be completed on 85% of its engines by 1/1/85. Assuming retrofits could start no later than early 1981, average engines would log the following hours: 4EWB - 9900; 3EWB - 9375; 2EWB - 9225; 3ERB - 9115; and 2ERB - 9600. On the basis of this, the average engine would not represent a problem. Outlyers, that is those engines that achieve very long TBO would, however, be a problem. Many mature engines achieve 20,000 hours between overhauls. LMI does not have any data upon which to estimate the number of engines of each type that fall in the outlyer (beyond engine hours flow) class. P&W's 15% of total engines seems much too high and LMI used 2.5% for wide body aircraft engines and 5% for regular body aircraft.

Table A-19 shows the calculation of the various potential penalty costs based on the factors presented previously. Table A-20 presents the cost of compliance under various assumptions for both U.S. and foreign carriers. Note particularly that an inadequate time for service tests carries a potential worst case cost of $700 million, of which $400 million would be incurred by U.S. carriers. The worst case maintenance situation with NME 84 engines would add an additional $570 million, of which $336 million would be incurred by U.S. carriers.

TABLE A-18. MINIMUM COST OF COMPLIANCE
(Millions of Dollars)

	World Total	U.S. Fleet						Foreign Fleet					
			Wide Body			Regular Body			Wide Body			Regular Body	
		Total	4ENG	3ENG	2ENG	3ENG	2ENG	Total	4ENG	3ENG	2ENG	3ENG	2ENG
NME 81													
Hardware	$ 110.2	$ 56.0	$ 16.5	$ 21.6	$ 6.2	$ 4.3	$ 7.4	$ 54.2	$ 24.8	$ 15.2	$ 6.2	$0.6	$ 7.4
Maintenance	130.8	64.7	22.4	30.5	8.8	0.9	2.1	66.1	33.6	21.5	8.8	0.1	2.1
Fuel Saving	105.2	52.3	21.9	25.0	1.2	3.1	1.1	52.9	32.8	17.5	1.2	0.3	1.1
Total	$ 135.8	$ 68.4	$ 17.0	$ 27.1	$ 13.8	$ 2.1	$ 8.4	$ 67.4	$ 25.6	$ 19.2	$13.8	$0.4	$ 8.4
NME 84													
Hardware	$ 676.0	$366.5	$121.5	$183.0	$ 62.0	0	0	$309.5	$181.5	$128.0	0	0	0
Maintenance	201.2	110.1	34.9	55.8	19.4	0	0	91.1	52.1	39.0	0	0	0
Fuel Saving	64.2	34.4	12.4	16.0	6.0	0	0	29.8	18.6	11.2	0	0	0
Fuel Penalty	11.6	5.7	2.9	2.2	0.6	0	0	5.9	4.4	1.5	0	0	0
Total	$ 824.6	$447.9	$146.9	$225.0	$ 76.0	0	0	$376.7	$219.4	$157.3	0	0	0
IUE 85													
Hardware	$ 580.1	$395.6	$108.8	$112.2	$ 14.3	$105.7	$54.6	$184.5	$131.3	$ 38.5	0	$6.3	$ 8.4
Maintenance	200.3	126.9	44.9	51.5	15.5	8.7	6.3	73.4	54.2	17.7	0	0.5	1.0
Fuel Saving	207.7	136.5	43.9	42.1	5.9	29.2	15.4	71.2	52.7	14.4	0	1.7	2.4
Total	$ 572.7	$386.0	$109.8	$121.6	$ 23.9	$ 85.2	$45.5	$186.7	$132.8	$ 41.8	0	$5.1	$ 7.0
Total Program													
Hardware	$1366.3	$818.1	$246.8	$316.8	$ 82.5	$110.0	$62.0	$548.2	$337.6	$181.7	$ 6.2	$6.9	$15.8
Maintenance	532.3	301.7	102.2	137.8	43.7	9.6	8.4	230.6	139.9	78.2	8.8	0.6	3.1
Fuel Saving	377.1	223.2	78.2	83.1	13.1	32.3	16.5	153.9	104.1	43.1	1.2	2.0	3.5
Fuel Penalty	11.6	5.7	2.9	2.2	0.6	0	0	5.9	4.4	1.5	0	0	0
Total	$1533.1	$902.3	$273.7	$373.7	$113.7	$ 87.3	$53.9	$630.8	$377.8	$218.3	$13.8	$5.5	$15.4

TABLE A-19. PENALTY COSTS
(Thousands of Dollars)

Premature Removal (IUE 85)

	Engines	Factor	Premature Engines	Cost per Engine	Total Cost
4EWB	725	.025	18	$37.8	680.4
3EWB	1020	.025	26	25.8	670.8
2EWB	130	.025	3	25.8	77.4
3ERB	3020	.05	151	17.0	2567.0
2ERB	1560	.05	78	17.0	1326.0

Combustor Life (NME 84)

	Engine Years	Maintenance Increment	Total Cost
4EWB	1194	92.7	$110,684
3EWB	2230	75.0	167,250
2EWB	775	75.0	58,125

Service Test (NME 81/IUE 85)

	1981 Engines				
	NME 81	IUE8 5	Total	Cost per Shop Visit	Total Cost
4EWB	100	125	225	$180	$40,500
3EWB	160	120	280	160	44,800
2EWB	50	17	67	160	10,720
3ERB	72	440	512	85	43,520
2ERB	144	225	369	85	31,369

Service Test (NME 84)

	Engines Introduced						
	1984	1985	1986	Total	Shop Visits	Cost per Shop Visits	Total Cost
4EWB	150	65	65	280	430	$210	$ 90,000
3EWB	173	172	188	533	706	185	130,610
2EWB	62	62	62	186	248	185	45,880

TABLE A-20. COST OF COMPLIANCE UNDER VARIOUS CONDITIONS
(Millions of Dollars)

	Total	U.S.	Foreign
NME 81			
Minimum	$ 135.8	$ 68.4	$ 67.4
Service Test	136.0	70.0	66.0
Worst Case	$ 271.8	$ 138.4	$133.4
NME 84			
Minimum	$ 824.6	$ 447.9	$376.7
Service Test	493.5	266.8	226.7
	$1318.1	$ 714.7	$603.4
Combustor Life	569.2	336.1	233.1
Worst Case	$1887.3	$1050.8	$836.5
IUE 85			
Minimum	$ 572.7	$ 386.0	$186.7
Premature Removal	6.7	5.3	1.4
	$ 579.4	$ 391.3	$188.1
Service Test	144.8	100.9	43.9
Worst Case	$ 724.2	$ 492.2	$232.0

APPENDIX B

ESTIMATES OF COST IMPACTS

Prepared for LMI

by

Pratt & Whitney Aircraft Group

15 December 1977

ESTIMATED ECONOMIC IMPACT OF PROPOSED EPA EMISSIONS REGULATIONS FOR AIRCRAFT

December 15, 1977

Prepared for

LOGISTICS MANAGEMENT INSTITUTE
4701 Sangamore Road
Washington, D. C. 20016

PRATT & WHITNEY AIRCRAFT GROUP
Commercial Products Division

UNITED TECHNOLOGIES.

EAST HARTFORD, CONNECTICUT

SECTION 1.0

INTRODUCTION

The following pages present the economic data requested by the Logistics Management Institute in support of their study on the economic impact of proposed revisions to the aircraft engine emission standards. Pratt & Whitney Aircraft is strongly committed to the importance of conducting such a study as a part of the rule making process and has attempted to provide as complete and accurate economic data as possible.

Combustors have not yet been developed to meet the proposed 1981 and 1984 requirements, and, therefore, considerable uncertainty remains concerning whether or not these requirements can be met. For cost estimating purposes, a success-oriented scenario has been assumed and is described in Section 2. However, it is important to note that the actual economic impact of the proposed requirements is very sensitive to both the timing of the development effort and to the complexity of the ultimate combustor configuration.

Tabulated development cost estimates, newly manufactured engine price increment estimates, information for calculating retrofit costs and the value of associated loss of inventory, and maintenance cost estimates are presented in Sections 3, 4, 5, and 6, respectively. Brief explanations of the factors and specific assumptions used for each set of data are included with the tabular data. Section 7 provides a discussion of the effect of the regulations on fuel consumption and weight.

SECTION 2.0

ASSUMED SCENARIO USED FOR COST AND PRICE ESTIMATES

2.1 INTRODUCTION

The cost and pricing estimates presented in Sections 3 through 6 are predicated on assumed scenarios for the development and implementation of reduced emissions combustor concepts. The technology required to meet the proposed regulations is not in hand, and it is impossible to predict the time required to obtain it. Therefore, we have assumed for estimating purposes that the requirements will be adjusted consistent with the technical achievements and the implementation dates will remain as proposed. The specific assumptions and their effect on the cost and pricing estimates are discussed in Section 2.2.

The estimates also require a preliminary definition of the ultimate combustor hardware to define costs for production hardware and retrofit kits and to estimate maintenance costs. We have assumed that the technical approaches now being pursued are representative of the ultimate designs with respect to complexity and materials. These approaches are summarized in Section 2.3.

2.2 ASSUMPTIONS AND COMMENTS ON PROPOSED RULES

2.2.1 1981 EPA Requirements

The development of JT8D and JT9D combustors with reduced emissions of carbon monoxide and unburned hydrocarbons was begun several years ago and significant reductions have been obtained. A design has not yet been found, however, which simultaneously meets the proposed 1981 emissions requirements as well as the requirements for control of combustor exit temperature distribution, engine starting and altitude relighting, and combustor durability. In the development time now remaining, it is not likely that emissions can be significantly decreased, and experience indicates that some compromise in emissions may be necessary to obtain acceptable production configurations. In addition, the current timing does not provide sufficient time for a three-year service evaluation which we feel is necessary to properly develop the design for commercial service.

The assumption made for estimating purposes (and currently being used for program planning at Pratt & Whitney Aircraft) is that development work will be successfully completed to permit certification of the reduced emissions combustor by the end of 1978. On this basis, service test hardware would be available beginning in 1979. Production incorporation would occur two years later leaving insufficient time for an adequate service evaluation program. A one year deferment in the proposed regulation would extend the time available for service testing and would tend to minimize the danger of increased early maintenance costs.

2.2.2 1984 EPA Requirements

The proposed 1984 regulations for the emissions of the oxides of nitrogen are extremely difficult to achieve practically and will require combustor design concepts that are radically different from contemporary combustors. It is our opinion that such radical changes in concept are not economically viable for incorporation in newly manufactured currently certified engines or derivative engines at any future time period. We believe these combustor concepts and the regulations of emissions of oxides of nitrogen should apply only to newly designed and certified engines in the 1990 time period. For the purposes of this cost study, however, we have had to presume that the EPA 1984 regulations of oxides of nitrogen emissions could be achieved with a staged combustion system.

Although Pratt & Whitney Aircraft's Experimental Clean Combustor developed under the NASA-sponsored Experimental Clean Combustor Program demonstrated emissions low enough to meet the proposed 1984 requirements, it did not meet the smoke requirements. The combustor also did not meet the requirements for engine starting and altitude relight characteristics, and serious coking problems were experienced. The design was also far more complicated than would be acceptable for commercial service. These deficiencies can be resolved, but probably only at great expense and at the cost of increased emissions. We believe that some relaxation of the 1984 requirements will be necessary. Further, the time required for development, even with the most success-oriented program, will be a minimum of six years, with the first two years being devoted to concept definition and the remaining period being devoted to engine development. This scheduling would leave no time for service testing and could result in costly early service experience. A more realistic schedule would provide seven years for development with two-and-a-half years for technology development. As a minimum, we recommend deferment of the regulation to 1988 to permit adequate service evaluation.

For cost estimating purposes, we have assumed a successful development program requiring six years of effort, resulting in introduction of new combustors on schedule but without service evaluation. Further, we have assumed that the burners ultimately developed in response to the 1984 regulations will not require extensive changes in the current engine nacelles or require recertification of the aircraft. If this occurred, this would be a very significant additional cost impact. We have also assumed that the regulation would not be applicable to growth versions of the JT8D combustor and therefore no estimates for a growth JT8D combustor meeting the 1984 requirements have been provided.

2.2.3 1985 Retrofit Requirement

The 1985 rule imposes emissions standards on in-use engines equal to those for 1981 newly manufactured engines. This rule will require retrofit of the in-use engines with the same combustor as used in the newly manufactured engines. Consequently, the comments and assumptions relating to the 1981 regulation presented in Section 2.2.1 are applicable also to the 1985 retrofit requirement.

2.3 TECHNICAL APPROACHES

2.3.1 Technical Approach for 1981 Newly Manufactured Engines and 1985 Retrofit Program

To satisfy the proposed 1981 EPA emissions regulations, it is assumed that the same technical approach will be adopted in the JT8D, JT9D, and JT10D engine programs. All three engines will employ new aerated fuel nozzles.

Combustor airflow schedules will be modified to provide approximately stoichiometric burning for high combustion efficiency at idle power. The gas temperature distributions within these combustors will be different from that in current production combustors, and cooling airflow modifications will be required to ensure adequate combustor liner durability.

The reduced-emission JT8D combustors represent comparatively small modifications to the current production combustors. All models (JT8D-9, JT8D-15, JT8D-17, and JT8D-209) will employ aerated fuel nozzles such as shown in Figure 1. These nozzles incorporate a pressure atomizing primary and an aerated secondary fuel supply. All models will also incorporate a modified dome, revised cooling air distribution, and modified combustion and dilution hole patterns in the liner, as shown in Figure 2. The combustor liner dilution hole patterns for the JT8D-15 and JT8D-17 engines, which have cooled high-pressure turbines, will be different from those for the JT8D-9 and JT8D-209 engines, which have uncooled turbines, since the combustor exit temperature profiles must be different.

The modifications required to the JT9D-7 engine are shown in Figure 3. The fuel nozzle will be the dual-pipe aerated nozzle similar to those discussed for the JT8D engines. A major change will be required in the front end. A bulkhead front end will be substituted for the current front end, which consists of twenty short cones. The bulkhead combustor will require increased length fuel nozzle supports as well as a new hood, revised mount pin arrangement, and new ignitor locations. Modifications to the liner cooling air distribution and combustion and dilution hole patterns will also be needed.

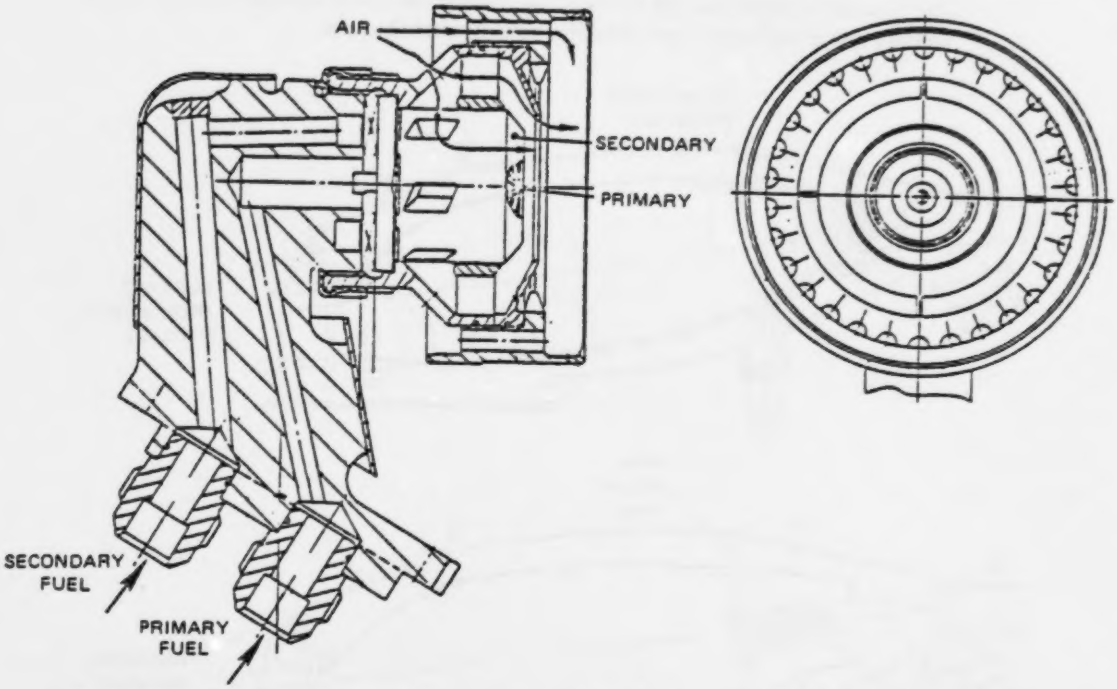

Figure 1 *Dual-Pipe Aerated Fuel Nozzle Design Concept - Nozzles of this type were assumed for meeting the 1981 EPA requirements for JT8D and JT9D engines.*

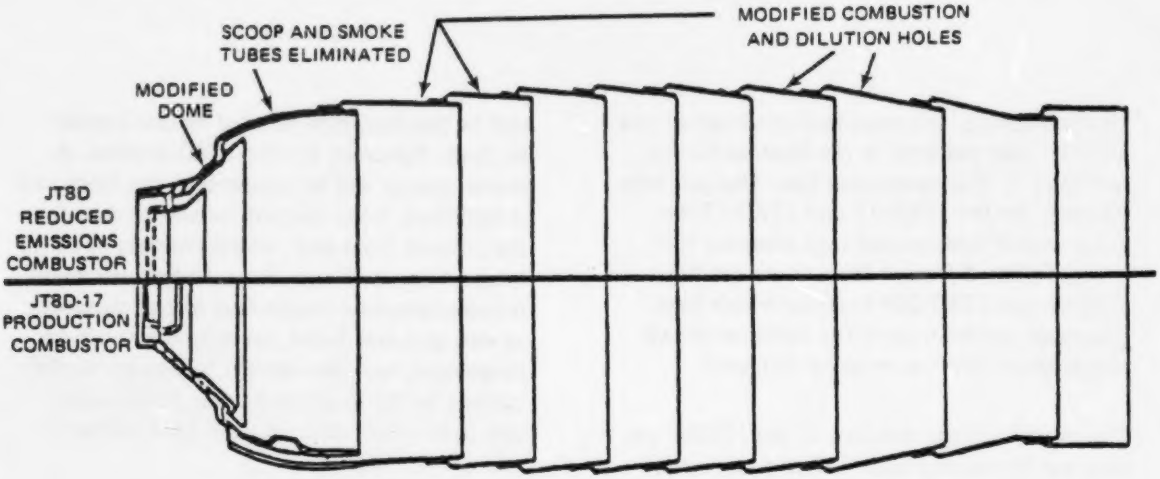
MODIFIED COMBUSTION AND DILUTION HOLES
SCOOP AND SMOKE TUBES ELIMINATED
MODIFIED DOME
JT8D REDUCED EMISSIONS COMBUSTOR
JT8D-17 PRODUCTION COMBUSTOR

Figure 2 *Modifications for JT8D Combustor to Meet 1981 EPA Requirements - Relatively small changes will be required to change the front end configuration and modify the combustion and dilution airflow distribution.*

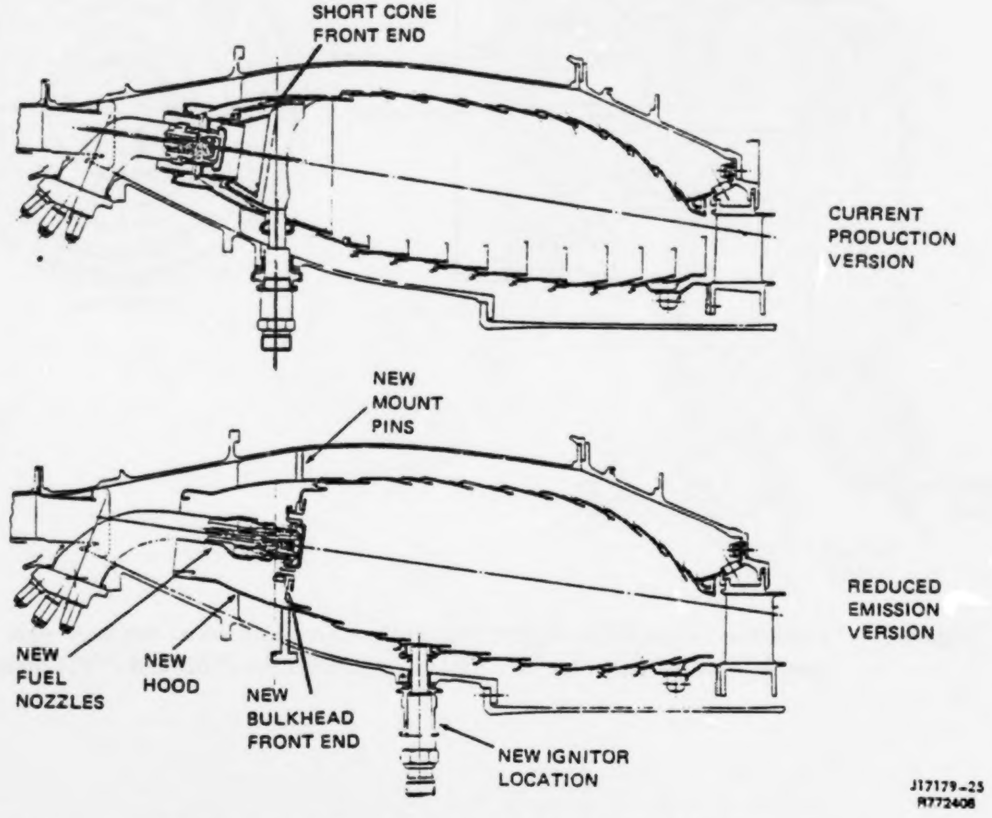
SHORT CONE FRONT END
CURRENT PRODUCTION VERSION
NEW MOUNT PINS
REDUCED EMISSION VERSION
NEW FUEL NOZZLES
NEW HOOD
NEW BULKHEAD FRONT END
NEW IGNITOR LOCATION
J17179-25
R772408

Figure 3 *Modifications to JT9D-7 Combustor to Meet 1981 EPA Requirements - The JT9D-7 combustor requires a major modification to incorporate a bulkhead front end and relocate the ignitor.*

For the JT9D-70 engine, the major modification will be the incorporation of the new aerated fuel nozzle and its support. This engine already incorporates a bulkhead combustor. Other modifications will include redistribution of the combustion and dilution air, revisions to the liner cooling air schedule, and the addition of support pins to maintain the louver tip spacing to maintain combustor durability.

The JT10D engine is expected to incorporate a bulkhead-type combustor and a simplified single-pipe aerated fuel nozzle.

The approach assumed for the retrofit program is that retrofit kits consisting of new sets of aerating nozzles, new liners, and other necessary hardware will be provided to convert the in-service JT8D and JT9D engines to the same configuration as the newly manufactured engines.

2.3.2 Technical Approach for 1984 Newly Manufactured Engines

A commercially acceptable approach for meeting the 1984 EPA requirements has not been identified. However, the lowest emissions of oxides of nitrogen were demonstrated in a two-stage Vorbix (vortex burning and mixing) combustor tested under the NASA-sponsored Experimental Clean Combustor Program. Therefore, this design approach was assumed for cost estimating purposes. Regardless of the specific design, a multistage combustor is probably required to provide low emissions over the total engine operating range.

The combustor tested under the Experimental Clean Combustor Program is shown in Figure 4. It consists of two axially displaced stages with ninety fuel nozzles. The upstream stage or pilot zone has 30 pressure atomizing fuel nozzles with concentric axial swirlers mounted in a bulkhead front end. This stage is designed to operate at stoichiometric fuel-air ratio at idle power. At high power, this stage provides hot gases to vaporize the secondary fuel. Sixty pressure atomizing fuel nozzles inject secondary fuel into a high velocity throat section between the pilot and secondary zones.

Immediately downstream of the secondary fuel injectors, secondary air is introduced through circumferential rows of swirlers in both the inner and outer liners.

A similar design was assumed for the JT10D combustor, and cost estimates were made by scaling the JT9D configuration to the size and operating conditions of the JT10D engine.

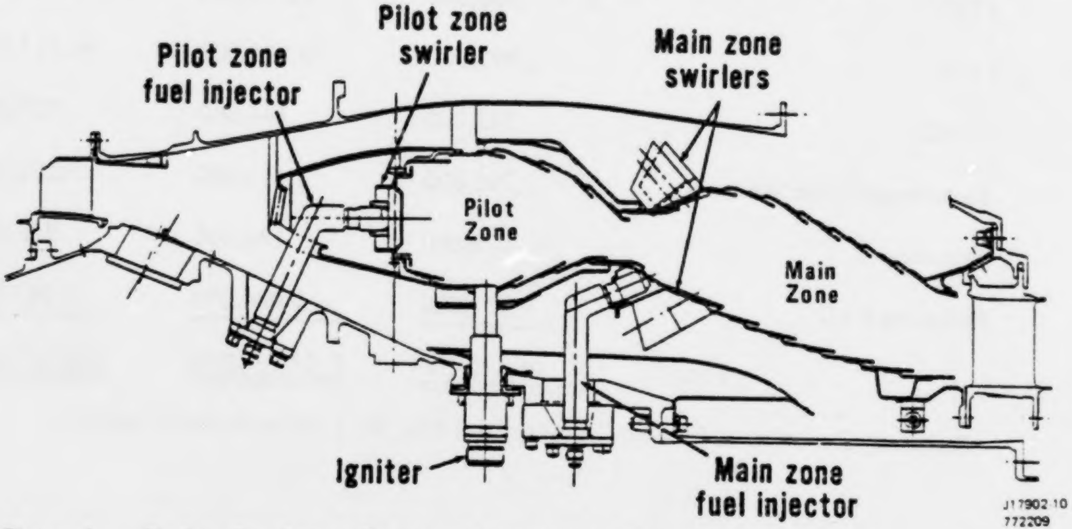

Figure 4 Vorbix Combustor Tested in Experimental Clean Combustor Program - A two stage combustor of this type has been assumed for JT9D and JT10D engines to meet the 1984 EPA requirements.

SECTION 3.0

DEVELOPMENT COST ESTIMATES

The expenditures for the development of reduced emissions technology to date are presented in Table I. The table represents an updating of data presented to the EPA in February 1976 covering expenditures through 1975. As shown, total expenditures projected through December 1977 for reduced emissions technology development are $40,815,000 for the categories shown.

Estimated future expenditures to meet the proposed 1981 and 1984 EPA requirements are shown in Table II. As shown, a major effort of nearly $250 million has been assumed. As discussed in Section 2, this development effort is a very high risk program. In addition, changes in the required emission levels or the implementation schedule could significantly alter these estimates.

With regard to the service evaluations, it should be noted that the estimated cost for meeting the 1981 regulations includes costs for a two-year service evaluation consistent with the implementation schedule assumptions. For the 1984 regulations, time is not available for the desired three-year service evaluation, but the cost of such an evaluation has been estimated for reference. Service evaluation would not be planned for the JT10D combustor since the JT10D engine will be a new engine, and service evaluation is appropriate only when a new component is introduced into a mature engine.

TABLE I

DEVELOPMENT EXPENDITURES TO DATE TO REDUCE ENGINE EMISSIONS

	Through 1975*	1976 and 1977	Total Through 1977
JT8D	$ 1,088,000	$ 6,978,000	$ 8,066,000
JT9D	2,992,000	13,325,000	16,317,000
JT10D	583,000	144,000	727,000
Technology Contracts	3,790,000	1,412,000	5,202,000
Proposals	772,000	184,000	956,000
Emissions R&D	7,451,000	2,096,000	9,547,000
Total	$ 16,676,000	$ 24,139,000	$40,815,000

*Previously Reported to EPA on February 26, 1976. All costs in then-year dollars.

TABLE II

ESTIMATED FUTURE DEVELOPMENT COSTS TO MEET EMISSIONS REQUIREMENTS

	Thousands of Dollars (1978 Dollars)				
	1981 EPA Requirements		1984 EPA Requirements		
	JT8D	JT9D*	JT9D*	JT10D	Total
Engine Design and Analysis	$ 440	$ 980	$ 9,370	$ 7,740	$ 18,530
Engine Hardware	545	2,290	47,200	52,645	102,680
Engine Tests	4,140	12,750	36,410	26,490	79,790
Rig Tests	1,200	330	8,500	14,600	24,630
Service Evaluation	330	2,180	10,680**	0	13,190
Program Management and Reports	435	980	3,600	3,490	8,505
Totals	$7,090	$19,510	$115,760	$104,965	$247,325

Notes:

* Includes both JT9D-7 and JT9D-70 models

** Cost estimate provided for reference. The assumed scheduling would not permit service evaluation of the 1984 combustors.

SECTION 4.0

NEWLY MANUFACTURED ENGINE PRICE INCREMENT ESTIMATES

The price increments estimated to result from meeting the 1981 and 1984 EPA requirements in newly manufactured engines are shown in Table III. The price increments are based on the assumption that the technical approaches described in Section 2.3 will be successfully developed within the estimated development costs presented in Section 3.0.

The large estimated price increases for the 1984 engines are the result of characteristics inherent in a two-stage combustor, which we believe will be required to address the 1984 emissions regulations. The change from one stage to two adds considerable cost and complexity. For example, the two-stage combustor demonstrated in the Experimental Clean Combustor Program required ninety fuel nozzles, compared with only twenty in the current JT9D combustor. The two-stage fuel supply system is also considerably more complex and costly than a single-stage system.

TABLE III

ESTIMATED PRODUCTION PRICE INCREMENT FOR NEWLY MANUFACTURED ENGINES RESULTING FROM PROPOSED EMISSIONS REQUIREMENTS

	Estimated Production Price Increment (1978 Dollars)					
	JT8D-9	JT8D-15	JT8D-17	JT9D-7	JT9D-70	JT10D
1981 EPA Requirements	$14,100	$11,700	$8,000	$ 50,800	$ 45,700	N/A
1984 EPA Requirements	N/A	N/A	N/A	$309,300	$309,400	$299,300

N/A - Not Applicable

SECTION 5.0

RETROFIT COST ESTIMATES

Affected in the retrofit program will be all JT8D and JT9D engines delivered by December 31, 1980 to domestic airlines and foreign airlines operating in the United States. Table IV provides a breakdown by model of the affected engines expected to be in service by the end of 1978. Airline Transport Association or FAA forecasts can be used to predict expected increases during 1979 and 1980.

The cost of the retrofit program involves a number of factors beyond the price of the retrofit kit. If the retrofit is performed in conjunction with other hot section maintenance, the cost of the retrofit would be minimized and would consist of the kit price and the cost of related shop labor. Based on current development and production program schedules, the earliest that retrofit hardware can be expected in quantity would be 1982, providing approximately three years for the retrofit program. On the basis of projected shop visit rates for hot section maintenance, an estimated 90 percent of the affected JT9D engines and an estimated 85 percent of the JT8D engines could be retrofit in conjunction with other hot-section maintenance during the first two years of the program.

The remaining engines would require scheduling into the shop specifically for retrofitting during 1984. For these engines, the cost would consist of the kit price; the cost of line maintenance personnel to remove the engine from the wing and, following retrofitting, reinstalling the engine; the cost of shop personnel to disassemble the engine, modify the combustor, and reassemble the engine: and the cost of performing certain routine maintenance operations prior to their normal schedule because of the retrofit requirement.

Our estimate of the costs and manpower requirements for the retrofit program for each engine model on a per-engine basis are presented in Table V. Total estimated costs can be calculated after applying the appropriate labor rates for airline maintenance personnel.

Kit prices were estimated on the basis of the hardware definitions presented in Section 2.3.

TABLE IV

ESTIMATED NUMBERS OF ENGINES REQUIRING RETROFIT COMBUSTORS IN SERVICE ON OR BEFORE DECEMBER 31, 1978

Engine Type	Engine Models	Number of Engines
JT8D	1, 7, and 9	4,311
JT8D	15 and 17	1,365
JT9D	3A, 7, and 7F	1,636
JT9D	59 and 70	94

Note: Includes domestic carriers and foreign carriers operating in the United States.

TABLE V

ESTIMATED COMBUSTOR RETROFIT COSTS AND MANPOWER REQUIREMENTS PER ENGINE

	JT8D-1/7/9	JT8D-15/17	JT9D-3A/7/7F	JT9D-59/70
RETROFIT IN CONJUNCTION WITH OTHER HOT SECTION MAINTENANCE				
Retrofit Kit Price (1978 Dollars)	$36,500	$33,000	$148,000	$184,600
Shop Labor (Manhours)	173	19	170	80
RETROFIT INDEPENDENT OF OTHER MAINTENANCE				
Retrofit Kit Price (1978 Dollars)	$36,500	$33,000	$148,000	$184,600
Line Labor (Manhours)	22	22	48	48
Shop Labor (Manhours)	278	124	530	395
Cost of Premature Maintenance (1978 Dollars)	$15,700	$18,200	$ 35,600	$ 40,200

Manpower estimates were based on analysis of the rework required for each engine model. For retrofits conducted independent of other hot-section maintenance, the average manhours required for engine disassembly and assembly to gain access to the hot section were included. Retrofit labor requirements are described in the following paragraphs.

The JT8D-1, JT8D-7, and JT8D-9 engines must be sufficiently disassembled to rework the transition duct and to replace all burner cans and fuel nozzle and support assemblies. This will require removal of the low-pressure turbine and exhaust case as a unit, the high-pressure turbine first-stage nozzle guide vane assembly, the split fan burner case, the burner case assembly, the burner cans, and the fuel nozzle and support assemblies. The outer transition duct and guides will require replacement by reworked parts. The fuel nozzle and support assemblies and all burner cans will be replaced with newly designed hardware. The engine will then be fully reassembled.

The JT8D-15 and JT8D-17 engines will not require engine disassembly to remove the transition duct. Only the transition duct guides will need to be removed for rework, and the burner cans and the fuel nozzle and support assemblies will be replaced.

The JT9D-3A, JT9D-7, and JT9D-7F engines will need to be sufficiently disassembled to remove the inner and outer burner liners and to remove the diffuser case assembly. This will require removal of the gearbox module, the low-pressure turbine module, and the exhaust case assembly as a unit; then removal of the high-pressure turbine, the inner combustion liner, and the first-stage turbine nozzle vanes as a unit; and then removal of the outer combustor liner. The diffuser case assembly must then be removed and stripped of all hardware so it can be reworked and heat treated. After the diffuser case has been reworked, the diffuser case hardware will be reinstalled and the engine fully reassembled using the newly designed fuel nozzle and support assemblies and the new inner and outer combustor liners.

The JT9D-59 and JT9D-70 engines will require only replacement of the inner and outer combustion liners and the fuel nozzle and support assemblies.

The applicable cost of performing certain routine maintenance operations prior to their normal schedule results from the common practice of performing sufficient maintenance whenever the engine comes into the shop for major work to ensure that it will not require additional shop maintenance for an extended period, usually 4000 hours or more. This work is performed regardless of how much life remains for the affected parts at the time the work is performed. From an overall maintenance viewpoint, this approach is extremely cost effective, but it does result in the premature removal or repair of certain parts. The prorated value of these parts should, therefore, be included in the cost of the retrofit work for those engines specifically scheduled for retrofitting independent of other hot section maintenance. The value used in the estimates presented herein was equal to 20 percent of the average cost of an engine shop visit for heavy maintenance. This percentage is based on an estimate of the remaining life of the engines scheduled into the shop specifically for retrofitting during the last year of the program. The dollar cost is based on airline data and includes the costs of material replaced, outside repair, and shop labor. The labor costs are based on 2300 manhours for each shop visit for the JT9D engine and 1500 manhours for the JT8D engine, calculated at $18.50 per hour. This rate is typical of airline shops and is not fully burdened.

Estimates of the spare parts inventory owned by airlines and overhaul shops lost through obsolescence have also been made. With careful management, shelf inventory could be depleted during the retrofit program to the point where its residual value would be negligible when the retrofit program is completed. In the worse case, however, it would be unlikely that the shelf inventory would exceed that required to support the engines entering the last year of the retrofit program without being retrofitted. As indicated previously, we estimate that the engines in this category will be approximately 10 percent of the JT9D engines and 15 percent of the JT8D engines. The value of this inventory on a per-engine basis was estimated based on the actual inventory practices for the parts being replaced. These values in 1978 dollars are $2200 for each JT9D engine and $690 for each JT8D engine. The total value may be calculated on the basis of Airline Transport Association or FAA estimates of engine fleet size.

SECTION 6.0

MAINTENANCE COST INCREASE ESTIMATES

The impact of the EPA requirements on maintenance costs was estimated for mature combustors. However, as noted in Section 2.2, the assumed development and implementation schedule does not provide the normal three-year period for service evaluation. Therefore, higher maintenance costs will be experienced during the early period following introduction of the low emissions combustors into service. Data has been provided to permit estimating this additional cost for immature combustors.

6.1 MAINTENANCE COST INCREASE FOR MATURE COMBUSTORS

Estimated increases in maintenance cost for mature low emissions combustors are presented in Table VI. Values for both the material and labor portions are indicated together with the totals.

The combustors designed to meet the 1981 EPA regulations are generally similar to those currently used and are, therefore, expected to have the same life when mature. Further, these combustors are of the same general level of complexity. Therefore, labor manhours to repair the liners and maintain the fuel nozzles would also be expected to be similar to those for current combustors. The maintenance cost increase for the low emissions combustors for the 1981 EPA requirement would result from the increased price of the burner liner. The fuel nozzles are not considered to be life limited and, therefore, would not affect the maintenance cost.

The combustor configurations required to meet the proposed 1984 regulations are not as well defined as those for meeting the proposed 1981 regulations, and the experience base for staged combustors is extremely limited. As a result, cost estimates associated with the staged combustors contain a number of uncertainties, particularly with respect to combustor life. For this reason, we have estimated the cost increases associated with the increase in complexity and the increase in combustor hardware price. We have then used these estimates to calculate overall increase in combustor maintenance cost based in one case on the assumption that the combustor life would equal that of current combustors and in a second case that the combustor life would be 50 percent of that of current combustors. For the latter case, we included the effect of reduced combustor life on turbine life.

TABLE VI

ESTIMATED INCREASE IN MAINTENANCE COSTS FOR MATURE COMBUSTORS RESULTING FROM PROPOSED EMISSIONS REQUIREMENTS RELATIVE TO PRE-1981 ENGINES

	Estimated Maintenance Cost Increase (1978 Dollars per Engine Flight Hour)						
	1981 EPA Requirements				1984 EPA Requirements		
	JT8D-1/7/9	JT8D-15/17	JT9D-7	JT9D-70	JT9D-7	JT9D-70	JT10D
Material	$0.10	$0.10	$2.30	$2.30	$4.90-19.00	$4.20-22.90	$5.90-19.20
Labor	0	0	0	0	2.80- 8.30	2.80- 8.70	3.00- 8.40
Total	$ 0.10	$0.10	$2.30	$2.30	$7.70-27.30	$7.00-31.60	$8.90-27.60

Note: Labor cost estimate based on labor rate of $18.50 per hour.

The increased complexity increases maintenance cost because of the increased number of manhours required for maintenance actions. For example, for the staged combustor, the increase in complexity was estimated to increase the number of manhours for a typical repair by 500 manhours.

Maintenance costs will also be higher because of the increased price of the staged combustor life-limited parts, these primarily being the combustor liners and the bulkhead front end.

The approach for reducing the emissions of oxides of nitrogen involves operating the combustor very lean. This is achieved by introducing additional air in the combustion zone, leaving less air for liner cooling. The combustor liners will therefore tend to run at higher temperatures and may have shorter lives. A reduction of 50 percent relative to conventional combustors is possible.

Our experience indicates that reduced combustor life also reduces turbine life. Partially deteriorated combustors produce localized hot zones that are detrimental to the turbine airfoils. Hence, any reduction in combustor life could also result in reduced turbine life and higher turbine maintenance costs.

Table VI presents the possible range in the estimated increase in maintenance cost. The lower value represents the increase in maintenance cost for staged combustors with lives comparable to that of conventional combustors, and the higher value represents the increase in maintenance cost for staged combustors with a life that is 50 percent of that of the conventional combustors.

6.2 MAINTENANCE COST INCREASE FOR IMMATURE COMBUSTORS

As discussed previously, the combustors designed to meet the 1981 EPA requirements will be introduced one year before adequate service evaluation can be completed. The combustors designed to meet the 1984 EPA requirements will be introduced three years before service evaluation can be completed. As a result, immature combustors will enter service and a period of increased maintenance cost will occur.

Immaturity could affect costs in a number of ways. For example, combustor life could be reduced, or turbine life could be reduced as a result of carbon particle erosion or temperature maldistributions. A recent change in a JT9D combustor put into production without service evaluation resulted in more than a 60-percent reduction in hot section shop visit interval. In this case, unanticipated carbon formation in the combustor caused severe high-pressure turbine airfoil erosion.

It is impossible to make a precise prediction of the costs resulting from introduction of immature combustors into service, but an order-of-magnitude estimate can be made by estimating the number of additional shop visits anticipated for these combustors and then multiplying by the average cost of each shop visit. For example, the anticipated average shop visit rate for the current JT8D and JT9D engines is about 0.37 visit per 1000 flight hours. If the shop visit rate were doubled for engines with immature combustors, each engine delivered in 1981 would experience one extra shop visit during the first year of service. Presumably, the experience gained during this year would be equivalent to the experience that would have been obtained during the third year of the recommended service evaluation. Therefore, the modifications made during the shop visits during this year would upgrade the combustors to mature status.

Similarly, for the combustors designed for the 1984 EPA requirement, doubling the shop visit rate for the engines delivered in 1984 would result in two extra shop visits during the three-year period required to gain sufficient service experience to define the mature combustor design. The engines introduced into service in 1985 and 1986 would each experience one extra shop visit.

The estimated cost of each shop visit is presented in Table VII. Combining these data with Airline Transport Association or FAA forecasts for delivery projections and estimates of the increased number of shop visits for each engine will permit calculation of the estimated total increase in maintenance cost associated with the combustor immaturity. The values presented in Table VII are based on the same information discussed in Section 5.0 except that the values reflect the higher cost of the low emissions burners.

TABLE VII

ESTIMATED MAINTENANCE COST DUE TO IMMATURE COMBUSTORS

Estimated Maintenance Cost per Shop Visit (1978 Dollars)					
1981 EPA Requirements				1984 EPA Requirements	
JT8D-1/7/9	JT8D-15/17	JT9D-7	JT9D-70	JT9D-7	JT9D-70
$83,300	$90,800	$178,000	$200,900	$201,600	$222,400

SECTION 7.0

OTHER ENGINE CHARACTERISTICS

The impact of the proposed emissions regulations on fuel consumption and engine weight was assessed.

The assessment indicated no change in thrust specific fuel consumption with the combustors designed for either the 1981 or the 1984 regulations.

A weight increase would occur for the combustors designed to meet the 1984 regulations, but no weight increase was identified for the combustors designed for the 1981 regulations. The estimated engine weight changes attributable to the 1984 regulations are shown in Table VIII.

TABLE VIII

ESTIMATED INCREASE IN ENGINE WEIGHT
RESULTING FROM PROPOSED
1984 EMISSIONS REQUIREMENTS

	Weight Increase (lb)
JT9D-7 Engine	280
JT9D-70 Engine	300
JT10D Engine	200